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An approach on reliability and related concepts - maintainability and availability

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AN APPROACH ON RELIABILTY AND RELATED CONCEPTS - MAINTAINABILITY AND AVAILABILITY

BY

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I certify that all material in this dissertation which is not my own work has been identified and that no material is included for which a degree has been previously conferred upon me.

The contents of this dissertation reflect my personal views and are not necessarily endorsed by the University.

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To my family

ABSTRACT

This paper examines reliability, maintainability and availability concepts. These are defined and given some guidelines for their achievement including specific considerations for maritime equipment. For any of those concepts practical programs for field application are described. An overview about reliability data, including either its sampling and treatment, is also given. Finally some helpful statistical techniques are introduced as well as their application in reliability engineering.

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INTRODUCTION

The main objective of this dissertation on reliability and other related concepts, maintainability and availability, is to give a global view of those concepts but avoiding their mathematical treatment. However, some references on statistics and probability applications are included. The author had two basic reasons to choose this subject

1. The increasing role of quality and related concepts in Portuguese industries and other activities mostly because of the new European economic market in 1992.

2. Better personal understanding of which considerations lead to the implementation of optimum maintenance procedures.

So this dissertation aims mostly at:

1. Giving a global view of the reliability concept;

2. Making the basic connections among reliability, risk and safety;

3. Joint reliability, maintainability and availability as a global concept in the achievement of quality;

4. Emphasizing the important role of data sampling and its treatment as an essential factor for:

A. design improvements;
B. safer and more profitable equipment's operation;
C. better communication among operators manufacturers and certification bodies.

5. Giving some guidelines for the planning of reliability, maintainability and availability programs and their applications.

6. The role of standardization in the achievement of quality.

Most of these points are not deeply investigated because of:

1. Lack of documentation;

2. Documentation not updated;

3. Not easy to get documentation from manufacturers and others;

4. Many books and manuals make either a very theoretical treatment or are more or less repetitions;

5. Few bibliographies in these concepts.

The reliability in the maritime field is developed specifically when confident documentation is available. Therefore there were no books available so the sources were mostly a number of articles and reports from some specialized magazines. However, when the maritime industries are not mentioned it is supposed that ideas and concepts can be applied to them taking into account the existent constraints and particular environmental conditions.

The reliability and related concepts will have growing applications in all areas of industry being a recent engineering activity. Their development will have great impact upon:

1. Design optimization;

2. Safer operations;

3. Reduction of maintenance levels;

4. Less spare parts used in time and number;

5. Better production quality.

However, reliability has many random factors associated with it but the prime mover for its application are either cost / benefit considerations or safety considerations. Reliability will have an important role for the achievement of increasing control of man over machine.

CHAPTER ONE

Risk, Safety and Reliability

1.1 - Risk and Safety

The concept of risk and its assessment has a very important impact on the reliability level of equipment, systems and human networks. Risk can be defined as the potential hazard that people or equipment are subjected to when performing their functions or missions. The target when dealing with risk is keeping it at the lowest level meaning what was accepted either by project partners or by a Society. In all cases, the acceptable risk should be defined, for example, capital costs due to stoppage of production, human casualties, loss of ship's control, etc.

There have been many situations where the risk supported by customers is very high not due to the manufacturer's fault but just because of the late development of the technological or scientific knowledge. The application of asbestos in many industrial processes, after an extended use was considered a potential source of health risk to human beings. So many research procedures were carried out leading to the development of new products. New environmental and industrial protective legislation was also issued. This is a practical example of risk assessment and how to keep it at an acceptable level.

The function or mission of many people, mostly in industry and public administration, is really keeping risk at an acceptable level. This is usually carried out under the context of cost and benefit. However, the benefit should not just mean a money process but an increasing involvement to avoid: human casualties, pollution, radiation and limitation of all potential sources of risks.

At present the treatment of risk concepts is not only a question of equipment concept and its development of design, that is to say, finite elements, new materials, new production methods, fuel burning efficiency, interface man and machine. So the emphasis must be made among mankind, society, industry and envirónmental requirements. Here can be pointed out the case of diesel engines, where mechanical reliability developments increases either the availability or reduces the mechanical risks of failure. However, this process is going along with the technological developments trying to keep the noxious emissions at acceptable levels so limiting the environmental risk.

Although the engineering methods have had an important impact on environmental conditions, it is not the objective of this paper to make this analysis but it is supposed that the application and development of reliability engineering will give some useful help to this field.

Risk has been assessed in an engineering sense so engineers have to evaluate it during design phases long before a product or equipment leaves the production department for customer delivery. During the design process, depending on the kind of equipment, all risks by using them must be assessed in detail. The engineering design team must analyze the risks either of the primary functions or those of the secondary functions. This means assessing the design as a whole and issuing correct specifications. Nevertheless, in this approach should also be considered the following points:

1. Interfacing between subsystems;
2. Interfacing with environment;
3. Classification of hazardous severity;
4. People and equipment;
5. Mission;
6. Potential hazardous conditions.

Reliability and safety levels should be evaluated at the design stage. However, they become an intrinsic part of equipment at the following phases of manufacturing and quality control. The operational phase is the testing phase. During all these phases risk must be kept at levels defined in design specifications. In field operations the risk can be limited if the following points are observed

1. Correct maintenance.

2. Environmental conditions defined at design
   A. Temperature and pressure
   B. Humidity
   C. Radiation
   D. Working conditions
   E. Load
   F. Operational cycle
   G. Operator capacity
   H. Vibration.

From the above operator capacity must be mentioned. The correct role of education and training for the labour force in charge of both operation and maintenance duties must be the best method to maintain high levels of safety and reliability during the equipment life cycle.

Particularly concerning safety and reliability, it sometimes seems we are facing analogous concepts, because they are concepts whose boundaries seem to interact to some degree. However, they have an important joint role to avoid failures or to keep them at acceptable levels during the equipment life cycle. This means from the point of view of reliability the achievement of intrinsic reliability (mechanical equipment) or getting the highest mean time between failures. Safety is more concerned with loss of property and human casualties, but mostly equipment failures lead to these situations. In some well-defined situations these concepts are conflicting, for example, from the point of view of safety when a piece of equipment should be shut down. However, on the other hand reliability claims that the application of a certain level of maintenance and optimization of operations must restore reliability levels and fulfil the safety demands. Correct maintenance and correct operation are essential in keeping reliability and safety at acceptable levels and getting the most out of what was defined at design and manufacturing phases.

From the view of safety either failures or potential conditions to failure are not evaluated at the same level of importance. It is important to distinguish them according to the level of probability to cause casualties, taking special consideration if human beings are involved.

To clarify this concept the following case is an example. Some equipment has been sold with a very low level of reliability introduced either in the design phase or during the manufacturing process. This type of equipment is generally found on the market at very low prices. However, that does not mean that all expensive ones are safe and reliable. Poor designs are usually strong sources of risk and are discarded at first failure because of the big potential damage and very high repair costs. Much of this equipment, because of its low safety level, is a potential source of risk to all consumers considering mostly the electrical and fire hazards. Some other industrial equipment is generally a potential risk to people directly involved in the operations or processes.

The equipment during its useful life does not keep itself at a fixed level of safety introduced at the design and manufacturing phases, even with correct operation and maintenance. So the safety margins degrade with time, just considering its useful life span. Thus risk increases naturally during the equipment life time. However, the increasing rate of degradation is kept under control if the equipment's operational specifications are observed.

1.2 - Risk Evaluation and Standardization

Risk evaluation of equipment has an increasingly important role on design. It is during this phase of the conception process that the right moment to keep the hazardous failure probability at the acceptable level.

This is the time to give emphasis on the selection of the basic safety features that mean trying to eliminate most of the potential hazardous sources. Firstly, by designing intrinsic safety and secondly, by applying safety devices. The target is to avoid hazardous failures leading to very high costs both in property and human life. During this phase all materials must be specified accurately to support the existing working conditions.

At this point such factors such as, load, torque, stress, strength as well as the safety factor or safety margin, according to environmental conditions must be estimated. Other considerations, in risk evaluation and acceptable safety requirements are the establishment of correct safe devices to avoid hazardous working conditions to eliminate the casualties during operation. The control of dangerous fluids, protection barriers not allowing free access to the machinery's moving parts, relief valves and warning devices are very important measures to avoid potential hazardous conditions.

According to the importance of equipment or systems the risk assessment will have more or less importance in the design process and when essential specialized engineering knowledge and skill to make accurate estimates of risk involved must be used. All people involved in operational activities must be well aware of all the risks involved in executing their tasks and how to act in case of any hazardous situation. Here it is very essential to have good information as well as good training.

Evaluation of risk is not a new subject. Large amounts of data have been collected from the historic records of a huge quantity of equipment and systems. At present this process has been speeded up by widespread use of informatics and communications which allows the development of large databases, mostly in very critical areas of industry. Electronics, automation and high tech fields have the highest priorities. However, for the time being all industrial fields are more or less receiving advantages from the use of databases. Data, to be useful, needs a very hard work in sampling, selection, treatment and analysis. However, this is a non stop task due to the continuous up-dating. So all this information is a very helpful tool for decision-making to cope with risks. Nevertheless, in some industrial fields risk remains as an important factor of concern.

In many areas of activity, the knowledge that has been obtained is translated in technical legislation and guidelines at the national and international levels leading to the operational standardization of methods, materials, safety measures, reliability evaluation. This technical legislation and guidelines are usually called "standards". However, they are not the most advanced specifications that could be achieved in all areas of activity. In many cases they are only the minimum of technical acceptance but even at this level they are very powerful tools. Acceptance is generally reached with agreement among various technical partners such as, professional associations, governments, industries, unions and independent experts.

Standardization is primordial in getting the minimum of safety and quality from engineering procedures and commercial operations. In industrialized countries there is a very strong emphasis in the standardization process.

However, the worldwide dissemination of standards is made by international organizations. Among others must be referenced the International Maritime Organization, International Standards Organization and International Electrotechnical Committee which are responsible for important improvements in many engineering areas focusing on safety protection. This process goes very deeply into economic reasons at national and international levels. Using the worldwide acceptable standards it is really possible to use the same technical language with all the advantages involved.

In the standardization process in the maritime field the relevant role play by the International Maritime Organization and the classification societies as worldwide regulating bodies in safety and related areas must be pointed out. However, these classification societies are also important partners in developing of rules and guidelines for industries ashore.

1.2.1 - Standards in Reliability Engineering

In some industrialized countries, for example, France , Japan, U.K., U.S.A., Germany, a certain number of reliability standards some of which are included in maintenance and quality control fields have been issued.

In France, some reliability standards have been issued by AFNOR and included in the industrial maintenance field. Some of these standards are mentioned briefly below.

1. Standard X60-502 - December 1986
   "Operating reliability and after sales service".
   At that time this standard was not yet discussed at ISO meetings.

2. Standard X06-501 - September 1984
   "Terminology relating to reliability, maintainability and availability".
   This standard, with some modifications, is a reproduction of IEC publication 863/1986.

3. Standard X60-503 - November 1985
   "Initiation into availability"
   At IEC no international standard about this subject exists.

In the U.K. many standards from civil and military sources have been issued - British Standards and Ministry of Defense Standards. Among other things some of them because of their importance are mentioned below.

1. Ministry of Defense, Def.Stan.00-5
   "Design criteria for reliability, maintainability and maintenance of land service material"
   *Part1-General requirements
   *Part2-Mechanical aspects
   *Part3-Electrical and electronic aspects

2. Ministry of Defense, Def.Stan.00-41
   "MoD practices and procedures for reliability and maintainability"
   *Part1-Reliability design philosophy
   *Part2-Reliability apportionment modelling and calculation
   *Part3-Reliability prediction
   *Part4-Reliability engineering
   *Part5-Reliability testing and screening

3. Ministry of Defense, Def.Stan.00-40
   "Achievement of reliability and maintainability"
   *Part1-Management responsibilities and requirements for R & D programs and plans"

4. British Standards Institution, BS 3527
   "Glossary of terms used in data processing"
   *Part4-Reliability, maintainability and availability.

5. British Standards Institution, BS 5760
   "Reliability of systems, equipment and components"

*Part1-Guide to reliability programme management.
*Part2-Guide to the assessment of reliability.
*Part3-Guide to reliability practices: examples.

In the U.S.A. the worldwide prestigious standards called "US MIL-STD" have been issued. The British and international standards for reliability demonstrations are based on "US MIL-STD 781". The U.S.Department of Defense has issued three groups of standards about sampling plans and procedures for an equipment's life testing. However, a constant failure rate is assumed. They are:

1. H 108
2. US MIL-STD-690B
   "Failure rate sampling plans and procedures"
3. US MIL-STD-781C
   "Reliability testing for equipment development qualification and production".

MIL-STD-690B is a detailed standard concerning procedures for equipment qualification and production, running tests, failure rate records and quality requirements. MIL-STD-781C is applied to components testing in repairable equipment which is operating for periods of time, for example, electronic devices, automation controls, electric motors, etc. It is also useful for testing assemblies, systems or subsystems. All these assessments are based on the constant failure rate concept and, generally applied in electronic reliability.

1.2.2 - Overview of Reliability Standards and Methods Applied by Classification Societies

Here a brief interpretation how societies of classification are applying the reliability concept directly or indirectly is given. Among these are mentioned the American Bureau of Shipping, Germanischer Lloyd, Lloyds Register of Shipping, Bureau Veritas and Det Norske Veritas.

In ABS rules, reliability requirements are not specified directly in terms of either MTBF (mean time between failures) or MTTR (mean time to repair) but generally the rules are emphasized in the safe structural integrity of ships. However, in this society the role of quality control as an indirect important factor for achievement of reliability is highlighted. Regarding quality control, in ABS rules " ELECTRICAL EQUIPMENT"-section 35 and "SHIPBOARD AUTOMATION" and "REMOTE CONTROL"-section 41 must be point out. Testing requirements in the achievement of safety standards are important points in all rules either in testing components or systems and assemblies. They have important roles in indirect evaluation of the propulsion machinery availability. In all testing requirements the environmental conditions are focussed in detail the environmental conditions. For example, shipboard atmosphere conditions, heeling in all conditions of stability, temperature limits, humidity limits, variation of fundamental electrical parameters and vibration in terms of amplitude and acceleration. ABS rules are silent about quantitative reliability assessment for any shipboard system.

Germanischer Lloyd is applying reliability concepts in design of automation and equipment control to the engine room but there are no applications for the same type of equipment used in other ship areas. This society uses its own system for assessment and certification of reliability of shipboard automation equipment. There are several pieces of equipment tested for reliability:

- Main engine remote control;
- Emergency stopping and load reducing devices;
- Fuel and lubricating oil supplies;
- Electrical supply;
- Essential auxiliaries;
- Boilers and burners;
- Automatic controls;
- Fire detection systems;
- Alarm systems;
- Fault registration equipments;
- Engineer"s call system.

The reliability assessment of new automation systems are made during the six months before issuing the initial certification.
In rules of classification - RULES FOR THE CLASSIFICATION AND CONSTRUCTION OF SEAGOING STEEL SHIPS - the reliability requirements for automation equipment are addressed indirectly. However, the availability is accentuated by application of redundancy for components and systems. This society operates, in collaboration with shipping companies manual collecting data systems on equipment failures in the automation field. This data is processed, being a very powerful tool to assess the operational reliability onboard ships and to detect unreliable equipment. This data allows to select the manufacturers and to help them in upgrading their quality control standards, thus improving the fleet's safety.

DET NORSKE VERITAS has recognized reliability as an engineering discipline and it has engineering teams working in this field. However, among some reliability workers exist the opinion considering reliability not as a new engineering discipline but as just a helpful tool in many engineering fields.

Reliability has been used at DET NORSKE VERITAS with success as an independent engineering discipline. These techniques have been applied to large maritime equipment data bases, collected in a ship"s operation, getting at the same time important quantitative elements about maintainability and repairability. The reliability at component level has also been quantified. Reliability engineering work at DET NORSKE VERITAS is applied either to engine room automation equipment or to bridge and navegation equipment.

In "RULES FOR THE CONSTRUCTION AND CLASSIFICATION OF STEEL SHIPS", terminology associated with reliability engineering, for example, reliability, availability, MTBF, MTTR, etc are defined.

DET NORSKE VERITAS requires that all equipment manufacturers must submit to this society all technical documentation related to equipment reliability. Sophisticated databases about failures are managed by DET NORSKE VERITAS from onboard ships reports. This information has been used to conduct surveys and quantify reliability at systems and components levels. So it is also a good source of pressure on the manufacturers quality control methods.

The above methods of reliability engineering are not applied at "BUREAU VERITAS". However, the assessment of automation equipment has been done using indirect reliability concepts as the other classification societies mentioned above. Generally, reliability has been evaluated either by the capacity of recovery from some predicted failures or from the application of operational and environmental testing. This society has been treating manual data bases originated onboard ships that have been useful about type of failures, their occurrence and identification of unreliable equipment.

Below is given a brief list of environmental tests required by this society:

- Temperature test;
- Shock test;
- Vibration test;
- Heat and humidity tests;
- Salt fog test;
- Mechanical endurance test;
- Immersion test;
- Oil resistance test.

The last reference is LLOYDS REGISTER OF SHIPPING. Here reliability is identified at the system level rather than component level. The certification of automation equipment is issued considering the redundancy concepts in case of failure assuring ship's control. Reliability at component level is assessed using similar methods as in other classification societies. Reliability is applied using indirect methods and in "RULES AND REGULATIONS FOR CONSTRUCTION AND CLASSIFICATION OF STEEL SHIPS" there is no direct reference to reliability engineering concepts. However, the plans of automatic control systems submitted to LLOYDS should show clearly the system failures and their causes and effects.

LLOYDS has run databases of failures or casualties affecting ship's classification, however, the other events are not mentioned.

To summarize, only one of all societies mentioned above are applying direct reliability engineering techniques in equipment assessment. This gap is supposed to be eliminated in the near future. The achievement of reliability engineering in the classification rules is a powerful tool to increase operational safety and thus limit the potential hazardous risks.

CHAPTER TWO

Strategy for Reliability Achievement

2.1 - Concept of Reliability

Reliability is just a rationalization method used by mankind to build a long term masterpiece. Experience attained from using this method is kept in systematic, logic and economic ways. This means application of a scientific mode.

Reliability was born in the U.S.A. and U.S.S.R. to measure and estimate operational safety during space trips. Reliability aims at keeping quality during operations under recommended conditions.

All industrial equipment and the components tend to loose quality with time, mostly with operational time. The most well-known process of loosing quality is wear due to friction, abrasion and deformation. Other reasons are:

1. Mechanical stress;
2. Thermal energy transfer;
3. Chemical energy transfer;
4. Electrical energy transfer.

By one or more of above mentioned reasons industrial equipment has lost its initial quality.

Reliability can be defined more precisely as the equipment property to perform assigned functions while preserving its operating indices within the specified limits, during the required time or the period during it is intended to be in service. This property of equipment depends on: its resistance to failure, longevity of its components, suitability for repair and endurance.

Reliability should always be considered in close relation with the assigned operating conditions of the equipment. The reliability parameters will naturally differ in various conditions of operation.

Failure is the term applied when the operating capacity of a product is grossly violated. It is partial or complete. Complete means total lost of operational functions; although, partial can affect some components but there is operational capacity. The correct definition of those concepts is essential in operational reliability assessment.

Some products can be recovered after breakdown by repair and others are discarded. The latter case can include anti-friction bearings, most of the gears, transistors and resistances. A piece of equipment may consist of recoverable and no recoverable components.

Resistance to failure means that operating capacity can be preserved during a specified period of time, distance, cycles, consumption, etc.

Longevity is the property to preserve its operating capacity to the limit stated, with the intervals necessary for maintenance and repair. The limit stated is such a condition after which its further operation is impossible or impraticable. The longevity of a machine lasts as long as it can operate effectively or until it is out of order. A machine repaired many times, but still in working order, may be rejected due to its moral depreciation, when its further operation becomes unprofitable. This is because of its small efficiency as compared with new designs serving the same purposes.

Suitability for repair, is the property of equipment, when its condition is such that the failures can be prevented, detected and eliminated in good time by means of regular maintenance and repair.

These properties which determine reliability can be evaluated from a quantitative point of view. This is done by systematic control of equipment in exploitation, studying environmental and operational load effects, properties of materials and functional missions of systems and equipment as a whole as well as the separate components. The results are processed by using mathematical probability and statistical methods. So the principal indication of resistance to failure is the probability of faultless operation and the intensity of failure in a certain degree of statistical confidence.

Reliability has a very high value these days due to the dramatic increase of repair costs and maintenance during warranty periods, even in equipments of small value used on a large scale. Another point is the reliability influence on reputation and penetration of equipment in a very competitive market.

In the achievement of real service reliability it is very important that the customers definition of exact conditions under which they intend to operate their equipments is considered. It is essential to keep these conditions under control all the time and to avoid careless operation, for example, operator abuse. The correct exploitation of equipment is the only way to achieve all the intrinsic reliability quality introduced during the design and manufacturing steps. Thus, it is very important to have correct information about all project specifications which were prooved at testing trials.

Input of quality into products does not mean just reliability, but also the achievement of other features namely:

1. Technical characteristics and performances;
2. Maintainability;
3. Availability;
4. Durability;
5. Safe Operation;
6. Low Pollution Level;
7. Total Cost.

There are no clear boundaries between reliability and most of these items; however, there are balances and a mutual influence among them. Although, reliability parameters are very important in the assessment of quality during technological life time of equipment.

The engineering definition of reliability is a widespread concept, easily found in handbooks and technical literature and is generally an idea of survival; failure avoidance of equipment. It is associated with time and space limits and has also been looked at as the science of failure in an engineering sense. Therefore there are important random factors associated. Thus Probability and Statistics have an important role in its assessment.

Reliability should be assessed from quantitative and qualitative points of view and the level of reliability specified has to take account of the following:

1. Details;
2. Care in Production;
3. Correct Operation and Maintenance.

Correct evaluation of reliability parameters is essential because of:

1. Increasing Complexity of Equipments;
2. Smaller Components;
3. Problems of Maintenance Due to Former Conditions;
4. High Investments and their Related Risks.

At present, very few manufacturers and designers include in data performances values of reliability. However, indices and aspects of quality have been included in contract clauses, mostly through customer and administration pressure.

Although, probability and statistical tools have had an important role in reliability evaluation, it is important not to forget the engineering knowledge and common sense to avoid the reliability evaluation becoming a pure mathematical exercise out of reality. So, above all, reliability is an engineering process.

The reliability concept is increasing in its importance in equipment design; the reliability engineer as its skilled agent should have specific functions within the design team. However, this is not a golden rule for every piece equipment but depends on its importance in value.

It is during the design phase that it is decided how to input reliability into products. Therefore, after this decision has been taken, it is very costly to take any counter steps. The reliability achieved in product conception cannot be increased during operational explcitation but by manufacturer and designer intervention. However, reliability parameters are not fixed figures for all the operating life span. That is to say they

Change with time;
- Depend on type of equipment (mechanical or electronic);
Depend on operational conditions (loads and environmental loads);
- Depends on maintenance procedures.

If a product shows poor reliability during operation, three reasons can be pointed out basically:

- Poor maintenance planning and procedures;
- Abuse in operational conditions;
- Poor design conception.

Reliability evaluation has also feedback functions. It is very important to all manufacturers to know how their products have performed in operational conditions; the customers have responsibilities to feedback correct information. This information is paramount, with correct screening, because of:

1. The Redesign Process;
2. Future Development of Similar Products;
3. End of a Production;
4. Improving Sells;
5. Improving Technical Investments.

Here the use of standards to facilitate all this technical process should be mentioned. At present, in some countries, reliability standards have been issued which combined with general engineering standards will facilitate most of those items above. Reliability standards have been also extended to data treatment but sometimes just as guidelines. Reliability items that are receiving an increased standardization process are namely

1. Definition of technical basic concepts on reliability, that means use of the same technical language;
2. Procedures to reliability allocation in the design process;
3. Probability and statistical methods in evaluation;
4. Connections among reliability and other engineering concepts such as Maintainability, Durability and Availability;
5. Methods and procedures in collecting, selecting and analyzing reliability data.

There are some standard forms, available in some countries, which allow quick feedback from customers during operation. This process can be called after sales reliability assessment mostly for warranty procedures. Thus it is paramount to follow equipment performance during the operational life times. However, it depends on the type and importance of them. Reliability is allocated in the design process at different levels depending on the equipment importance. Therefore aircraft engineering reliability has a leading role in design, because any failure will mean very high risks in lives and property.

Otherwise in cheap domestic appliances, where risk in normal operation is very low, the reliability is not an important factor in design. Reliability allocation depends mostly on how the investments in reliability will be rewarded during the equipment's life time. So there are always cost and benefit implications in reliability allocation.

2.2 - Reliability Engineering Programs

Reliability is a growing engineering activity but this also means legal and adequate certification to its legal practice. Certification is done in several specific technical subjects and must be achieved by either examination or specific course attendance followed by examination. Some of these technical subjects are:

- Reliability definitions and how they are related;
  Analytical and numerical math methods;
- Specific use of statistical distributions in reliability evaluation;
- Failure functions;
  Methods of reliability testing and assessment;
- Products life cycle characteristics.

Reliability engineers must be in charge of the following functions:

1. Prediction and estimation of reliability from data obtained either by experimental testing or

information of operational use;

2. Participation in design process;
3. Allocation reliability among componente in complex equipment to get correct overall level of reliability;
4. Implementation of testing procedures in reliability assessment of products;
5. Application of probability and statistical methods in treatment of collected data;
6. Control of materials and products from suppliers according to specifications;
7. Warranty reliability evaluation.

The tasks of reliability engineering are concentrated in prevention, detection and correction of design deficiencies related to reliability. These tasks are also applied to weak parts, defects and poor workmanship in the manufacturing process. It must be pointed out, again, the necessity of collecting the correct data in the operational phase of equipment. Reliability engineering is, above all, an integral component of the design process and its improvement.

Reliability engineering procedures should be identified by a program including all life phases of any product, for example, design and redesign, production, operation and retirement.

In design and redesign, reliability engineering helps in defining objectives for the project. Input and output are focussed in problems that have been met in similar projects and the solution methods applied: this is a realistic approach for any new design. Reliability engineers thus help the design team to avoid errors in the following items:

1. Specifications of materials and components;
2. Definition of manufacturing process;
3. Comparison of several design options from the reliability point of view.

From experience gained in former projects records should be kept about difficulties that had been found in the development of similar equipment. In design phase reliability engineering agents are used as advisers not as a design approval authority. In the case of prototype testing, reliability engineering has responsibilities in all procedures. Data collected from tests must be used as an important source either to redesign or development of equipment. In testing the following points should be taken into account:

1. Not acceptable performance, for example, speed, consumption;
2. Weak components which are creating early failures;
3. Other desirable changes.

In the manufacturing phase reliability engineering should have an important role to help the control of production quality. Reliability allocated in former design steps can be degraded during the manufacturing process due to:

1. Poor selection of tools and machines, for example, precision, tools type and quality, etc;
2. Poorly trained workers;
3. Material and components not following the

specifications.

At this phase, reliability and quality control are integrated activities. The achievement of quality in the manufacturing process needs very skilled workers and the application of adequate training programs. In these training programs the role of quality in production must be stressed. In operational phase, an information feedback program from customers must be established. It is very important to collect data from the equipment applied according to specifications so these are the reliability field proofing procedures.

As was mentioned in this paper the manufacturers should have well-defined methods of getting and treating information, not only during the warranty period but also during all life cycles. It is necessary to underline the customers role in this process. However, they also have advantages in this process, namely:

1. Identification of failures and their origins;
2. Identification of poor design equipments;
3. Proposal of corrective measures;
4. Improvements in warranty clauses;
5. Better confidence among customers and manufacturers

If those corrective measures are taken the reliability engineering agents have to follow up those changes. Operational data regularly collected provides valuable historic records which will be used later on either to development of similar equipment or as a reference for new ones.

2.3 - Planning Reliability

At present it is normal for some big industrial companies to develop their own reliability engineering programs for their equipment. These programs are developed according to real conditions found in the environment, mostly customers needs and time experience. The importance and refinement of reliability programs depends on:

1. Complexity of products;
2. Safety and risk involved;
3. Health hazards;
4. Capital costs and benefits.

Some reference to reliability standards has been made that has been issued by some organizations. One of those standards, MIL-STD-785, can identify seventeen tasks to develop a reliability program.

In industrial companies, functional elements influencing product reliability are spread all over the organization. However they have different roles. For example, some create and develop reliability others keep up reliability so they have either direct or indirect influence.

To implement a program is necessary to identify what the influence of each functional element is to achieve a real reliability program. This influence should be

1. Top management planning:

Influencing contract clauses focussing on reliability, workload, personnel assignment and budget allocation.

2. Technical operations control:

Taking steps in critical technical activities and corrective actions implementation, for example, reliability growth control, failure control and materials review.

3. Data analysis and statistics on reliability:

Here can be included:
A. Reliability prediction and estimation;
B. Reliability assessment;
C. Field statistics;
D. Warranty data;
E. Reliability trend analysis;
F. Statistics simulation configuration;
G. Practical probability theory applications;
H. Cost of failures analysis;

4. Engineering functions:

These include:
A. Design;

B. Materials;

C. Manufacturing;

D. Field.

In the engineering functions some reliability related activities can be selected, for example:

A. Life time cost studies;
B. Reliability modeling;
C. Fault tree analysis;
D. Stress and strength analysis;
E. Tolerances estimation;
F. Wear and degradation analysis;
G. Critical items reliability;
H. Design review;
I. Effects of storage and shipment;
J. Maintainability previsions;
K. Parts standardization and testing;
L. Control of non-standard items.

E. Supplying and After Sales:

All supplies in parts and components should have a tight control from the reliability point of view. This is done applying both the minimum acceptable standards and testing programs.

2.4 - Reliability in Marine Industries

The role of the classification societies in defining the reliability requirements of marine equipment was mentioned in the first Chapter. Generally the reliability requirements have been emphasized for both electronic and automation items. However, there are other agents, that in one way or the other, have or will have direct or indirect influence in reliability achievement. These agents are:

1. Naval Architects;
2. Designers and manufacturers of maritime products;
3. Operators and Shipowners;
4. Maritime Administrators.

At present, reliability is not considered a paramount technical engineering discipline in the marine environment. However, reliability has had more acceptance in the Navy than in the Merchant Marine.

Reliability requirements are generally not specified directly by shipowners and shipbuilders but otherwise the manufacturers have started to give some emphasis to those points. Manufacturers are improving their reliability specifications trying to overcome the other competitors. Some of them have achieved the goal, for example, the fierce competition either in two stroke diesel motors or in the interfacing of two and four strokes, including increasing reliability considerations. The widespread use of reliability engineering will be essential for: higher profits, the highest level of availability in all operational conditions, increasing safety with very low levels of manning.

The Maritime Administration, applying adequate regulations or guidelines, has an important role in imposing more strict rules in selection of maritime equipment and structures keeping always an eye on safety improvements. There are some reasons leading to the implementation of reliability programs at the Maritime Administration level, namely:

1. Ergonomics and manning considerations;
2. Technological improvements;
3. Cost considerations.

On the first point either the sharp decrease of manning in ships or the number of working hours per crew member must be taken into consideration. Also to be taken into consideration is the adequate crew certification; it is not possible to keep a ship safe and reliable if the crew is not skilled for the job.

Maintainability is also another factor contributing to ergonomic improvements in ships. However, the biggest impact on first point is due to the quick development of both automation and complexity of the onboard ship systems. From a technological point of view the increasing interdependence among all technical systems set up onboard ship should be emphasized.

At point three, the technological improvements should mean intrinsic reliability or the highest mean time between failures; that is to say the achievement of the highest availability in all ship operations. Thus it is possible to get more successful ship operations and keep the internal and external risks at minimum levels.

The above considerations show the importance of introducing the reliability and its related parameters in rules and guidelines regulating the activities of all maritime agents. The Maritime Administration must consider the need of some developments in the above-mentioned items carried out in the following steps:

1. General survey of the equipments troubles;
2. Recording of failures and faults;
3. Repair costs;
4. Analysis of equipment used in similar jobs but in different locations;
5. Maintainability characteristics;
6. Knowledge of specifications and warranties at the acquisition process.

With complete information about these points and using reliability assessment procedures it will be possible to improve the efficiency of rules and guidelines by either introducing some statements or practical methods for reliability achievement. That is to say:

- Determination of reliability profile of equipment and structures;
- Increasing the understanding of influence of both specifications and warranties upon reliability;
- Better coordination among maritime agents;
- Simplification of repair procedures reducing the mean time to repair;
- Reducing the failure frequency and increasing the ship's availability.

If the Maritime Administration has established a reliability program it is very important to be aware of environmental developments and maintain a follow-up program of evaluation.

The shipowners should also have great responsibilities in the procurement of reliability, following the above indicated guidelines. But for them, the decisions for reliability achievement must pass essentially the cost / benefit considerations. However, to take good decisions it is necessary to be aware of the meaning of reliability in terms of a ship's operation efficiency. Without this evaluation it is not possible to issue the specifications required in contracts; that is to be aware of the direct and indirect allocation of reliability in all ship's systems.

Reliability allocation does not mean very high initial costs to shipowners, however, the bill is higher but will have very interesting rewards. This higher investment always has to be evaluated in future terms, taking account of the life cycle costs plus the initial cost. In practice, the reduction in total cost is mostly due to lower operational and maintenance costs and higher availability. This concept can also be applied to existing ships or equipment, with some small investments mostly in maintenance, for example, spending some money in maintenance monitoring instrumentation can give some rewards in terms of using the design intrinsic reliability more efficiently. Besides the correct specifications, shipowners, should also discuss with shipbuilders the details of warranties, in view of getting more reliable equipment. This can be seen as a way to achieve more confidence in new constructions. However the warranty time is essential. The time warranty extension works as reliability proof in terms of early failures so is determinant for the random failure equipment, for example, electronic equipment.

The operators, on behalf of the shipowners, have also increasingly responsibilities in keeping updated records of the systems and equipment performances onboard ships. These records are a very important source of information, not only for the technical department but also to other agents, for example, classification societies, designers and manufacturers of marine equipments, Maritime Administrations, etc.

The designers and manufacturers of marine equipment, generally apply reliability engineering procedures in marine automation otherwise it is not the rule in mechanical equipment. Such equipment is usually checked by using testing methods similar to those applied in other industries, for example, either running samples of equipment or components and recording the number of failures for a given period of time or running the test until getting a certain number of failures.

Testing will be accelerated or not depending on time factors. Before carrying out the test the reliability parameters to achieve must be specified. However, they will be accomplished or not, however, for acceptance there must be some statistical confidence level. The testing analyses are carried out either by statistical methods or by engineering analysis of the failed components. Thus these are the feedback methods of information for design and manufacturing developments.

The designers of marine equipment should facilitate the introduction of the reliability engineering achievements in all design steps according to both equipment importance and the safety requirements.

Another matter of concern that must be considered by the manufacturers is equipment warranties. In case of failure the liability will pass from the shipbuilders to the manufacturers. If the equipment has low reliability this will cause, to the manufacturer, higher costs and in extreme cases loss of the market share. The production of very reliable equipment gives more confidence to customers and also the warranty period will not be any source of concern. It can even be extended.

The shipbuilders should be prepared to face any reliability requirements from the shipowners specifications. In this case the reliability engineering must be functional in shipyards either when required in construction or when evaluating the equipment and materials ordered outside.

The shipbuilders must also be well aware of the reliability requirements that have been imposed by classification societies and other maritime agents. Some shipbuilders are well aware of reliability as a contract matter because of experience gained in Navy orders.

After all these considerations the increasing need of all marine agents to be aware of the real advantages given by applying reliability methods in their activities should be pointed out.

2.5 Designing for Reliability in Marine Equipment

The design for reliability in marine equipment, should take into consideration similar aspects of other equipment applied in other areas of economic activities. It is also essential, in the improvement of design, to consider the performance of the existing equipment for:

- Optimizing new design;
- Recovering existing equipment whenever it is possible;

- Reducing costs of maintenance and operation.

The procurement of these improvements do not just depend on the designer's efforts, but need the participation of the other agents. Shipowner participation is fundamental, by correct application of the scheduled maintenance and using the skilled crew in the ship's operation. This point must be understood as the feedback to designers. The introduction of the reliability engineering in design of marine equipment is a good help to finish the old conception and operational procedures by which the costs and the failure rates are not optimized. Some of these old points include:

- Incorrect assessment of the redundant and standby configurations;
- High maintenance staffs;
- Large stocks of spare parts.

Thus there are some measures that should be taken under the above mentioned conditions. Namely:

1. Be technically rigorous in the acquisition of any equipment and not careless about the warranty;
2. Choose the correct systems configurations considering the redundant and standby situations for safest operation;
3. Consider the correct layout of machinery and piping.

2.5.1 - Selectivity in Acquisitions

Standardization must have an important role in the acquisition process as a factor of intrinsic reliability. There are a few available reliability data about marine equipment, namely:

- Failure pattern;
- Repair costs;
- Operational costs;
- Readiness in maintenance procedures.

Some numbers on failure rates can be found. However, generally the confidence level is very low.

It is very important to pay increasing attention on maintainability factors in the acquisition process. Its optimization also depends on the correct assessment of maintenance costs in terms of both readiness and procedures in maintenance tasks. The correct allocation of the reliability and maintainability is an essential factor in the spare parts inventory optimization, so reducing the initial and operational costs. However, this must be balanced with the other future rewards.

The spare parts optimization means among other things:

- The minimum number of spare parts on board ship;
- An increase in quality;
- Better understanding about the type of failures and their frequency.

The statistical data on reliability and repair, as an important factor in the design feedback for improvements, have been under several constraints, namely:

- No widespread organized system for the data sampling and its analysis exists;
- Lack of interest;
- Lack of an adequate level of standardization;
- Big quantity of time and effort to collect the large Increase of the e;
- Increase in the equipment's complexity;
- Long distances and some communication constraints;
- The methods of sampling and recording are not the

The other two points that should be considered are: the life cycle cost and warranty in their connection to reliability factors. The evaluation of the life cycle costs should take in consideration the balance between initial cost and operational costs but is always necessary not to forget some aspects of the engineering value. The incorrect assessment of the engineering value is an essential factor leading to increasing unreliability: this means increase in life cycle costs. Thus it is essential to rank and allocate engineering value at design steps together with adequate reliability.

Another point to consider in the life cycle costs evaluation is the potential maintainability and its close association with reliability. The maintenance scheduling and procedures must be assessed to determine whether they are right to maintain the operational reliability and what it costs. Generally without the correct application of maintenance it is not feasible to keep the reliability at the foreseen design levels.

It should also be underlined that the maintenance procedures are carried out according to the different applications of the same equipment meaning the variation of both the maintenance planning and costs. Keeping life cycle costs at an optimum level means to follow the correct operational conditions, namely:

1. Do not exceed the design limits;

   If the operator exceeds such parameters as speed, temperature, etc, are conditions being created to failure;

2. Apply equipment in the environmental conditions that have been defined at the design phase;

3. Keep the correct safety margins;

   Due to both variation of the materials strength properties and loading conditions, if safety margins are not kept within correct limits increasing levels in failure rates, originating in the overlapping of strength and load, will occur;

4. Derating;

   This means reduction of the load factors below the nominal conditions, however, keeping the reliability at the foreseen levels and consequently reducing the failure rate.

If these basic conditions are respected reliability can follow the foreseen design levels. In practice it is usual for an increase of life cycle costs due to the operators abuse to occur this requires an adequate analysis but generally the following measures should be taken:

- Penalizing the operators;
- Increase in education and training;
- Use of skilled and qualified operators.

The last reference in the acquisition process is the warranty clauses which are essential either to the manufacturers and designers or to the customers. Increasing the quality and time in the warranty process will be more costly to the manufacturers, but if they succeed, they will certainly get a larger market share. However, if their equipment does not have the reliability required the warranty is always either a matter of concern for them or not involving clear business methods. Honesty is required in dealing with the warranty clauses and it must be avoided to pass the hidden costs from the manufacturers to the customers.

To get very good warranty clauses does not mean that the failure rate will be very low for all the equipment, however, some will show random failures, for example, electronic equipment.

Even if good quality control exists from the manufacturers this situation will not vanish but it is not generally a matter of great concern. However, some equipment has shown high failure rates during its initial life span and sometimes the application of good quality control by the manufacturer would be the right method to cope with that situation. Running in periods applied by the manufacturers can be a very effective measure to cope with bad quality. Generally the mechanical and electronic equipment has different behavior, from the point of view of failure rates, during the warranty period. In figure 1, the age reliability patterns of complex assemblies are shown.

As an illustration of the behavior of marine equipment during the warranty period a study on two and four stroke diesel engines is reported below. This study points out engine reliability and engine faults and their causes. This study is based in the sampling data from:

- 261 cylinders of two strokes main diesel engines;
- 240 cylinders of four strokes main diesel engines;
  918 cylinders of four strokes applied in electrical power generation.

The period of time reported is from July 1977 to January of 1982. The analysis was carried out by:

1. Comparing failures in three types of engines per 1000 cylinders;

   After analysis of data were drafted the following conclusions were found:

   A. Particular problems that had be given by the hot components in two stroke engines;
   B. Lower failure rate in four stroke engines may be linked to lower load;
   C. The fuel systems are important sources of failure rate in all type of engines, however four stroke engines have the highest failure rate. Fair number of failures were caused by poor design;
   D. High level of failures in pipes showing three state conditions - leaking, cracked and

corroded.

2. Influence of cylinder bore in failure rate of two strokes engines per 1000 cylinders:

Increasing failure rates were detected, caused by higher thermal loads, with the increase of the bore diameters, even with mean effective pressure in the range of 10.3 to 11.0 bar.

3. Engine performance parameters and service hours:

In figure 2, the number of failures per cylinder in two stroke engines are shown against the actual mean effective pressure. The failure rate increases steadily with the increase in the mean effective pressure but if some corrections are made according to the number of hours the curve inclination will be steeper.
There is a reduction of reliability with the engine specific load increase during the warranty period. This is due to the undesired effect of strength and load overlapping combined with thermal stress. Figure 3, shows the actual service hours per year plotted against the failure rate per cylinder. The values obtained are very low compared to those of the two stroke engines.

4. Cause of failures:

These were distinguished into five groups:

A. Design faults;
B. Material faults;

C. Machining faults;

D. Assembly faults;

E. Unknown faults, not including critical failures.

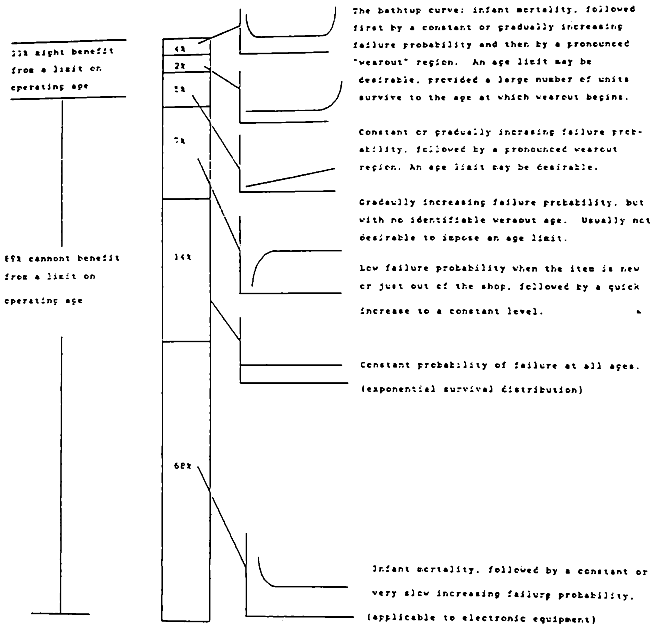
Faults due to bad operation are not included because the warranty does not cover them. Table 1 discriminates the essential failures either by number or by percentage. From the analysis of that table the important role of poor design leading to failure should be underlined. To overcome this situation it will be desirable to:

- Design optimization taking important care with design details;
- Be more aware of the environmental condition;
- Optimize the combustion process.

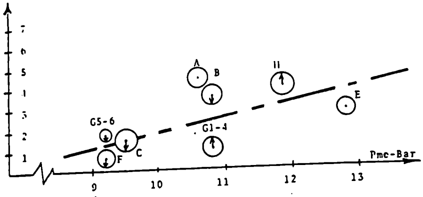
Finally it should also be pointed out, from Table 1, that the high failure rate in auxiliary engines is caused by poor material application.

2.5.2 - The Selection of Correct Systems Considering Redundant and Standby Configurations

In the first Chapter some brief references were made, about reliability existing in the rules of the classification societies, including the application of the redundancy principles whenever safety is the essential factor to take into consideration. Most of those references are done for automation systems.

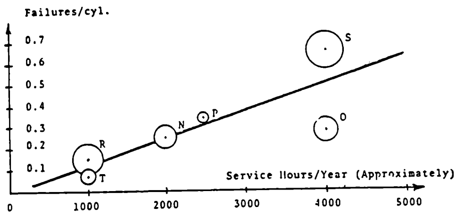


AGE-RELIABILITY PATTERNS FOR COMPLEX ASSEMBLIES



2-STROKE ENGINES (with design Pme ≥ 12,9 Bar)

—— Failures versus actual Pme during the guarantee period. Area of "dot" proportional to number of engines included.



4-STROKE AUX. ENGINES

—— Failures versus actual service hours/year. Area of "dot" proportional to number of engines.

TABLE	ESSENTIAL FAILURES IN NUMBER AND PCT (%)					
Cause of failures	2-STROKE PROPULSION		4-STROKE PROPULSION		4-STROKE AUX.	
	No.	%	No.	%	No.	%
DESIGN	260	45	62	36	55	26
MATERIAL	24	4	26	15	85	41
MACHINING	61	11	1	-	3	2
MOUNTING	69	12	15	9	13	6
UNKNOWN	162	28	68	40	53	25
TOTAL	576	100	172	100	209	100
TOTAL PR. 1000 CYLINDERS	2700		720		230	

Generally the development of redundant systems onboard ships depends on:

- Requirements of the classification societies;
- Requirements of Maritime Administration;
- Specifications given by shipowners;
- The state of the art.

The designers have free space to develop equipment according to their creativity and how much money the maritime agents want to pay.

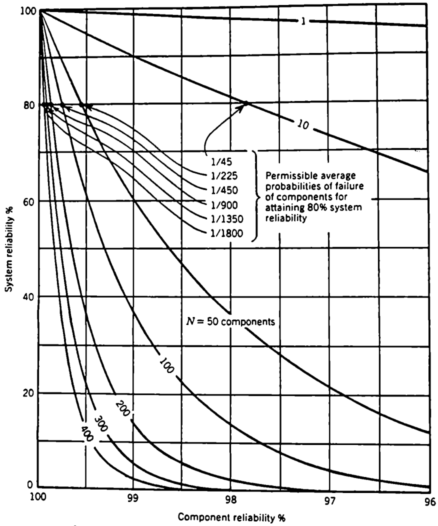
In the redundancy allocation process quantification of how much reliability must be inherent in any equipment, system and component should be made clear. However, this process should be done according to the hierarchy, from the lowest to the highest. According to the configuration defined the overall reliability parameters should be evaluated.

There are some design considerations in the procurement of redundant systems, namely:

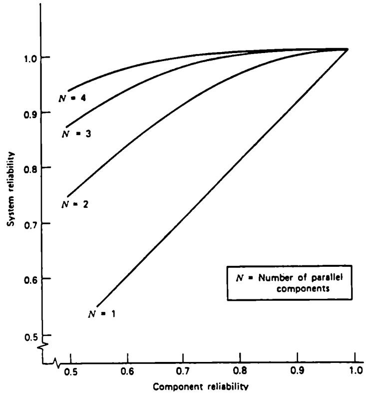
The failure of any component should be independent of any other one;

In figures 4 and 5, as can be seen, in theory, overall reliability varies as a function of the number of components and the individual reliability allocated, however, the theoretical overall reliability is not totally followed by the practical redundant systems;

Reliability increases according to the number of parallel components. Otherwise in series configurations the reliability decreases sharply with the increasing number of components;



System reliability as a function of number and reliability of components.



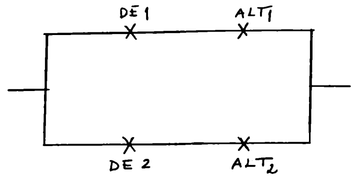
Reliability improvement by N parallel components.

power generation onboard ships but the very important point for its development does not focus on reliability. Waste heat recovery and unifuel concepts are the latest design developments leading to optimization of the shipowner's fuel bills. However, there have been some reliability design improvements leading to the reduction of failure rates and increase in availability. The configurations of electrical power generation systems found onboard ships are shown in figure 6.

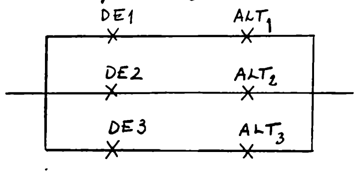
- System 1 has two subsystems, each of which includes one diesel engine and one alternator. There are no heat recovery considerations. The two subsystems are independent of one another.

- System 2 has three subsystems, each of which includes one diesel engine and one alternator. There are no heat recovery considerations. All subsystems are independent of one another.

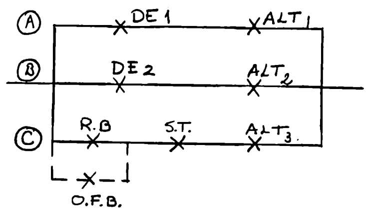
- System 3 has three subsystems. Branches A and B have one diesel engine and one alternator each. Branch C has -one recovery heat boiler, one steam turbine and one alternator; however, there is another redundancy option by the application of one oil fired boiler in parallel with the other one. All branches are independent of one another. At branch C there are more series elements affecting reliability to lower values. Even the application of an oil fired boiler does not mean an increase in overall reliability in all operational conditions. In this configuration there are strong considerations in waste heat recovery.



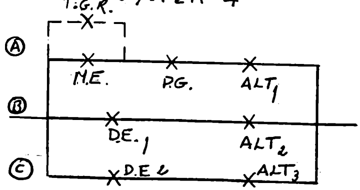
SYSTEM 2



SYSTEM 3



SYSTEM 4



DE – DIESEL ENGINE

ALT – ALTERNATOR

R.B – RECOVERY BOILER

O.F.B – OIL FIRED BOILER

S.T. – STEAM TURBINE

T.G.R – GAS RECOVERY TURBINE

M.E. – MAIN ENGINE

P.G. – PLANETARY GEAR

- System 4, in branch A has one planetary gear and one alternator (shaft generator). Branches B and C are two independent subsystems, each having one diesel engine and one alternator. All three subsystems are independent of one another. The reliability and availability of branch A is very dependent on the planetary gear and main engine. There is no exhaust heat recovery in this configuration however one exhaust gas turbine can be applied in parallel with the main engine. This configuration is very complex for reliability assessment, considering all the operational specific conditions - standby, in course, at anchor or in port. This configuration shows potential future developments in design with an increase in reliability.

Several considerations should be made for assessment of redundancy. First, one must define the operational conditions found by electrical configurations in ship service. Second, after defining these conditions it is possible to make a complete assessment for any condition - at sea, in maneuvering and in port operations. For any condition the following should also be considered:

- Number of generators running and on standby;
- Number of generators running and shut down for maintenance purposes;
- All generators running at maximum power, no existing redundancy available;
- All generators running at minimum load.

For a complete reliability evaluation of any configuration there are complexities caused by:

- Scarce data in failure rates of systems, subsystems and components;
- Complexity of systems caused by the increasing number of auxiliary elements necessary to work the main systems - pumps, heat exchangers, electronic devices, logic elements, etc;
- Time to achieve enough data from some systems, subsystems and components, for example, boilers;
- Lack of correct records either in operating times or repair times;
- Lack of data accuracy.

To summarize, reliability and availability are not at present the leading factors in mechanical design efforts so there has been more concentration on the optimization of configurations according to the heat potential available from exhaust gases. At this point it is essential to underline the increase in achievements that have been made in reliability and availability of command, control and regulation devices.

2.5.3 - Layout of Machinery and Piping

The optimization of the physical arrangements of either machinery or piping machinery is one design activity with room to be improved. These improvements are able to increase the reliability and maintainability standards as well as equipment availability.

The process of setting up any equipment onboard ship can affect its intrinsic reliability parameters either at coupling or in the assembly on site. Particularly, poor assembly can cause damage due to, for example, harmful vibrations and overstressed components.

There have been attempts from designers to reduce the volume of engine rooms, to increase shipowners profits due to the larger loading capacities available. Although the reliability and maintainability must be kept growing. This has to be achieved by:

- A higher pattern of standardization;
- Modular equipment and piping;
- Increasing accessibility to any item of equipment;
- Optimization of the maintenance procedures;
- Simplicity.

It is difficult to get accurate information about the reliability of piping and its auxiliary components. This is generally an issue of strong subjective judgement. Piping must be a matter of concern onboard ships because it is possible to arrive at the situation of having very reliable equipment but the piping misconception and its poor assembly leads to unreliability. Below are given some approaches to increasing piping reliability

- Use of standard components - materials, valves, flanges, etc;
- Assessment of piping welding by the use of modern monitoring methods;
- Piping flexibility to avoid unusual stresses either by vibration or thermal expansion;
- Use of the required safety margins;
- Use of correct materials according to the handling fluid;
- Quality control both during manufacture and assembly;

- Minimization of components in piping: increasing the numbers of series elements decreases reliability.

Some of these points are observed by the classification societies' rules. Generally the test items are:

1. Materials;
2. Strength;
3. Wall thickness:
   A. Required;
   B. Calculated;
   C. Minimum values Corrosion allowance;
4. Manufacturing tolerances;
5. Permissible stress;
6. Design pressure and temperature.

The welding of piping requires:

1. Edge preparation for the welded joints;
2. Alignment and assembling;
3. Preheating;
4. Heat treatment after forming and welding;
5. Non-destructive testing of the welds and acceptance criteria.

The hydrostatic tests required are:

- Individual testing;
- Testing after the assembly onboard ship;
- Testing of valves and fittings.

Reliability Relationships - Maintainability and Availability

3.1 - Introduction

Reliability is not the only concept affecting product quality. There are others, and among them can be found two with close connection with reliability - availability and maintainability.

Maintainability is a quality concept introduced and developed during the design phase and finally accomplished at the production phase. This is not pure maintenance or but is only a concept dealing with easiness in maintenance methods and procedures.

The role of reliability engineering is keeping the failure rate and costs associated at the lowest level while maintainability-engineering efforts are made for the achievement of optimum maintenance tasks at the lowest costs. Maintainability implementation is achieved basically at the design phase and complemented at the operational phase. Reliability and maintainability are recognized as complementary concepts with a strong influence on availability. Thus to obtain an adequate level of availability it is necessary to have:

- Adequate reliability;

Adequate maintainability;
Correct interaction between reliability and availability.

It is necessary to point out that the three concepts are not always well balanced in all equipment; this depends on the type of product and its application.

Availability is a very understandable concept even by the lowest rank operator; according to the popular perception of the idea. When the operator presses the pushbutton the machine will start or not, this means it is available or not. This implies a binomial condition, success or failure. The concept of availability is related to the following conditions:

1. The equipment in failure condition;
2. The equipment in repair;
3. The equipment waiting for repair;
4. Loss of power;
5. Change of the production cycle;
6. Standby;
7. Operation.

Most of these conditions are shown in the diagram of figure 7. This diagram also has the time allocation of RMA (reliability, maintainability and availability) parameters during the operational cycle. To summarize for a complete analysis of the operational cycle it is necessary to know:

1. The Functional Conditions

A. Operation

B. Standby

C. Real Down Time.

2. Time Conditions

A. Operating Time to First Failure.

B. Operating Time To Failure.

C. Operating Time Between failures.

D. Real Up Time.

E. Up Time.

F. Down Time After Failure.

G. Time to Restoration.

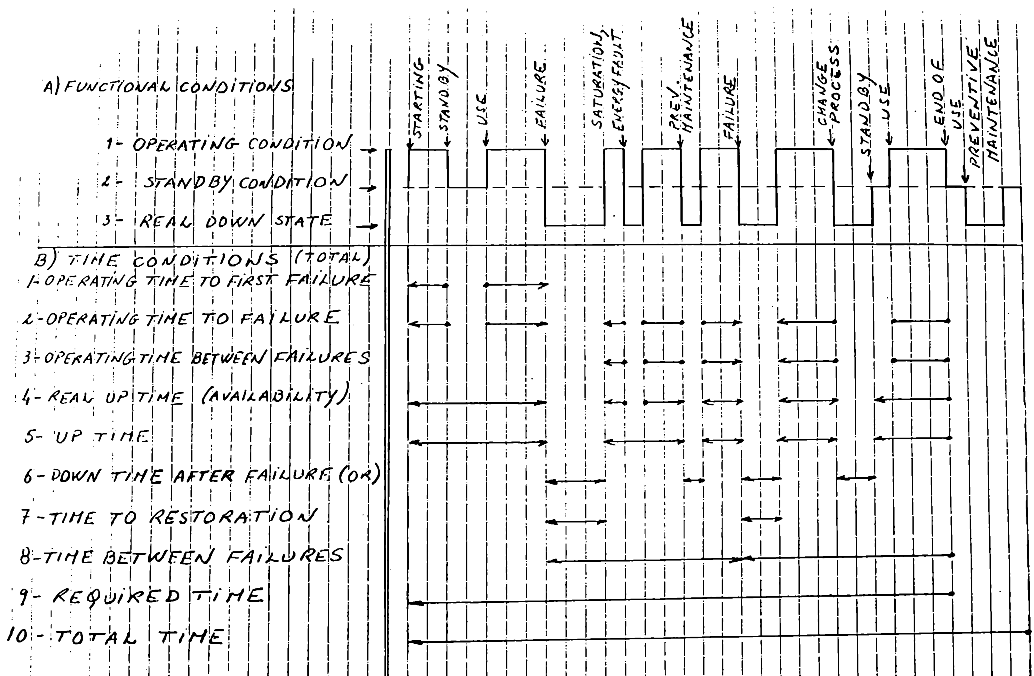
H. Time Between Failures.

I. Required Time.

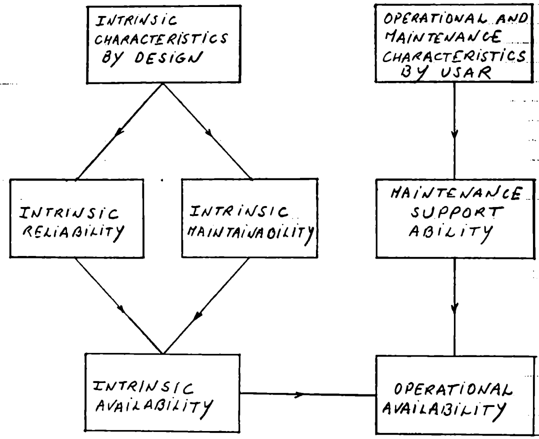
J. Total Time.

Some of these times are recorded at the equipment level, others are estimated from the record files.

In figure 8 for the achievement of operational availability the intervention of two agents, the designer and user, is necessary. The former is responsible by introducting both intrinsic reliability and maintainability during the conception phase and passing on to the manufacturing phase. The latter is in charge of the application of foreseen maintenance capabilities.



A) FUNCTIONAL CONDITIONS
1- OPERATING CONDITION
2- STANDBY CONDITION
3- REAL DOWN STATE
B) TIME CONDITIONS (TOTAL)
1- OPERATING TIME TO FIRST FAILURE
2- OPERATING TIME TO FAILURE
3- OPERATING TIME BETWEEN FAILURES
4- REAL UP TIME (AVAILABILITY)
5- UP TIME
6- DOWN TIME AFTER FAILURE (OR)
7- TIME TO RESTORATION
8- TIME BETWEEN FAILURES
9- REQUIRED TIME
10- TOTAL TIME
STARTING
STAND BY
USE
FAILURE
SATURATION, ENERGY FAULT
PREV. MAINTENANCE
FAILURE
CHANGE PROCESS
STANDBY
USE
END OF USE
PREVENTIVE MAINTENANCE


INTRINSIC CHARACTERISTICS BY DESIGN
OPERATIONAL AND MAINTENANCE CHARACTERISTICS BY USAR
INTRINSIC RELIABILITY
INTRINSIC MAINTAINABILITY
MAINTENANCE SUPPORT ABILITY
INTRINSIC AVAILABILITY
OPERATIONAL AVAILABILITY

3.2 The Integral Program for Prediction of the RMA Characteristics.

For prediction of RMA characteristics it is usually necessary to accomplish the following tasks:

1. Be aware of the initial conditions.

   For this is necessary to have:
   A. Functional characteristics of equipments
   B. Definition of types of failures
   C. Environmental conditions
   D. Operational conditions
   E. Determination of maintenance activities
   F. Conditions of maintenance logistic
   G. Program of quality / reliability.

2. Analysis of the RMA.

   These analyses are applied to:
   A. Reliability structure
   B. Constraints, for example, functional, environmental and operational.
   C. Maintainability characteristics
   D. Maintenance logistic.

3. Conception of either the structural or the mathematical models.

   These are carried out according to the degree of accuracy desirable, probability tools available and prediction level required. Typically, the following models are:

A. Structural model of reliability
B. Mathematical model of reliability
C. Structural model of maintainability
D. Mathematical model of maintainability
E. Structural model of availability
F. Mathematical model of availability.

4. RMA data sources analysis

In this phase the mathematical models to data sources are applied:
A. Reliability
B. Logistic of maintenance
C. Maintainability.

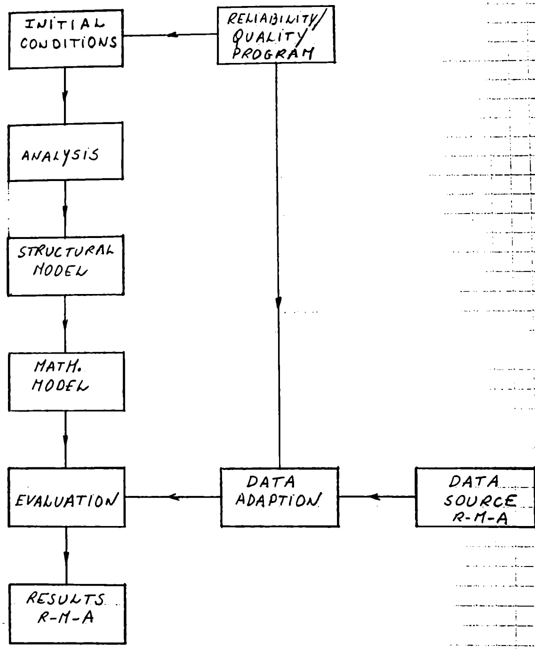
5. Evaluation and results presentation:

This last phase requires the quantification of RMA and its easy interpretation by all agents involved.

These five steps are represented in a simplified way in figure 9.

3.3 The Requirements in the Maintainability of Equipment.

Being a feature strongly linked to reliability in the RMA concept, - the importance of - making a brief analysis in this paper is understandable. Maintainability is closely linked to the idea of mean time to repair, which together with the mean time between failures, allows one to estimate the ratio of availability.


INITIAL CONDITIONS
RELIABILITY/ QUALITY/ PROGRAM
ANALYSIS
STRUCTURAL MODEL
MATH. MODEL
EVALUATION
DATA ADAPTION
DATA SOURCE R-M-A
RESULTS R-M-A

Maintainability due to its important influence in the equipment down time requires improvements in the standardization process and the development of a program of action. This program will be strongly influenced by the customers needs but its objective is to give a complete understanding of the maintainability factors in design and the correct evaluation of its objectives.

Before trying to underline the tasks necessary to develop the program on maintainability some of the basic points that must be emphasized for the maintainability achievement are given, namely:

1. The design criteria for maintainability;
2. The production of good sources of information about the maintainability capacity of equipment;
3. Allowing the build up of a good system to follow equipment performances in the field;
4. Advising the customers about maintainability management.

For the achievement of point one the following conditions are basically necessary to observe:

A. Use of standard components and sub-assemblies as the equipment's parts;
B. Use of standard elements either to couple or interface the equipment or systems;
C. Use of modular elements;
D. The minimum of components in the failure chain;
E. Use of built-in early detection failure elements, for example, application of condition monitoring;
F. Easy access of the maintenance instruments and tools

G. Good allocation of the recording instrumentation;

H. Keeping to a minimum the complexity of technologies applied in any equipment;

I. Correct ergonomics evaluation for accessing the equipment;

J. Limitation of the number and complexity of tools to disassemble any equipment.

K. Keeping at the minimum level the required adjustments.

Going beyond point two some elements can be identified the level of which may be developed depending on the type of user and the equipment complexity, they are:

A. The maintenance manual;

B. Trouble shooting guidelines;

C. The operational performances;

D. Diagrams and drawings of parts;

E. Disassembly procedures and tools;

F. Fluid types and consumptions;

E. Documents on the test trials for equipment acceptance.

In point three, some elements are included based on the after sales service quality; that is to say:

A. Reliable organization of that service;

B. Skilled staff;

C. Good location of the spare parts service therefore avoiding costly delay;

E. Warranty correctly specified and applied;

F. Delivery of small sub-assemblies so reducing costs.

In point four, the final one, the following must be pointed out:

A. Advice in any acquisition process to avoid the broad diversification of equipment and manufacturers;
B. Keeping the maintainability performances established at the design phase;
C. Optimization of the maintenance tasks;
D. Organization of the historic files on either preventive maintenance or corrective maintenance.

The historic files are an important source for the feedback of manufacturers allowing the correct evaluation of the equipment operability as well as the future development.

3.4 The Maintainability Program and its Evaluation

The target of this program is to reduce the costs during the product life cycle. Its achievement requires participation of both manufacturers and customers, therefore their participation depends on the importance of the project to be carried out and the project performances. The program requires detailed planning, procedures and tasks, along with the determination of responsibilities and the establishment of the correct logistics of maintenance. One good maintainability program gives to the manufacturer, for example, a better reputation and better market services against the competition. For users, this means namely, reduced logistics costs, reduced repair costs and easier maintenance.

Conception;

- Reliability engineering;
- Maintenance planning;
- Safety;
- Human factors;
- Manufacturing;
- Standardization;
- Definition of the system configuration;
- The engineering analysis value.

This program has to satisfy in terms of quantity and quality. The quality terms that can be identified are:

- Request of special instrumentation or tools;
- Request of special adjustments or regulation;
- Components standardization;
- Clear identification of the functional elements;
- Easy access for visual surveys;
- Use of built-in control devices;
- Correct identification of the control points;
- Correct codification and labelling of equipment and auxiliary elements.

The quantity terms that can be identified are the following:

- The logistics maintenance costs during the equipment life time;

PREVENTIVE MAINTENANCE	CORRECTIVE MAINTENANCE
- NUMBER OF OPERATION	- NUMBER OF OPERATION
- TYPE OF OPERATION	- TYPE OF OPERATION
- DESCRIPTION OF OPERATION	- TYPE OF FAILURE
- FREQUENCY OF OPERATION	- NUMBER OF WORKERS
- PROCEDURES OF OPERATION	- SKILLS REQUIRED
- NUMBER OF WORKERS	- TIME OF ACTIVE MAINTENANCE
- NUMBER OF MAN-HOURS	* DIAGNOSTICS
	* TECHNICAL DELAY
- TIME OF ACTIVE MAINTENANCE	* UP STATE RECOVERY
	* END CONTROL
- SKILLS REQUIRED	* TOTAL TIME
	* NUMBER OF MAN-HOURS

In the program development is necessary:

1. Preparation of the maintainability program planning.

   This document discriminates the management activities for achievement of maintainability inside and outside the organization.

2. Establishment of a review system concerning costs. This includes all extra costs originated by the project revision in terms of maintainability.

3. Determination of the maintainability allocation at subassembly level.

   Here must be taken in consideration the following:

   A. Global requirements of maintainability;
   B. Operational conditions and the logistics of maintenance;
   C. Availability of skilled maintenance personnel as well as adequate instruments and tools;
   D. Cost considerations.

4. The maintainability prediction and evaluation.

5. Building up the system of collecting and analysing data which will also be used for the decision of corrective measures.

   This data must be collected during the testing process as well as in the field operation.
   Testing procedures must be carried out according to application conditions including maintenance

logistics. The data collected has to be analyzed and the results compared with the quality and quantity specifications resulting in the required corrective measures will be taken or not.

6. Analysis of the simplicity of maintenance tasks.

From time to time experimental surveys should be carried out on the less reliable components and subassemblies for the evaluation of maintainability parameters. This process allows the detection of the needs for design improvements and also reformulates the maintenance support ability, for example, recommendations about the tools and instrumentation for reducing the down time.

7. Preparation of information for maintenance organization.

This means all the procedures carried out to schedule every maintenance task during the equipment's life time. For this it is necessary to consider the following:

A. Importance and frequency of the maintenance operations;
B. Requirements in special means, for example, specific tasks and special tools / devices;
C. Requirements in spare parts;
D. Number and qualifications of the maintenance personnel;
E. Prediction of the maintenance costs.

3.5 - Testing Maintainability

The operational maintainability is checked according to what has been defined at the conception phase. The methods used for the verification of maintainability, should be based on the following approaches:

1. Critical analyses at the design stage as well as in operation.

   These include the analysis of information that has been collected during the project development steps as well as in the later steps during exploitation. This can include the following assumptions:

   A. Complete external and internal identification and location of the equipment;
   B. The reasons for each maintenance operation;
   C. Number of workers, materials and spares used at any operation;
   D. The aptitude of the maintenance work force;
   E. The number of man-hours for each operation;
   F. Unavailability due to the maintenance operations;
   G. The operational time;
   H. Spare parts consumption;
   I. Devices, tools, and control instrumentation applied in the maintenance operations.

   The data collected at these steps may require the application of statistical tools.

2. Specific studies of maintainability.

These can include studies for simplicity of maintenance, optimization of maintenance operations and use of the simulation models. These specific studies carried out in the maintainability program are very important tools in reducing the costs and time of maintenance. The achievements are:

- Keeping the use of tools, devices and control instrumentation at the lowest level leading to less costs;
- Determination of the easiest access to each maintenance operation; less operational time;
- Optimization of space to carry out the maintenance tasks;
- Coordination of simultaneous tasks;
- Safer maintenance tasks.

3. Demonstration of Maintainability.

This includes the schedule of the tests to prove the maintainability parameters that had been specified by customers or significant to the potential customers. At this phase the statistical tools have been very helpful. In experimental testing either the preventive operations or the corrective operations must be carried out separately. However for each operation the mean time of intervention and the mean time of unavailability allocated must be recorded accurately. A very important point is the methods that have been chosen for failure simulation which must reproduce, as fairly as possible, the operational conditions. Among others these methods include:

- Deregulation;
- Internal or external disconnection;
- Cut of the fluids and the electrical supply;
- Removal of some internal components.

3.6 The Availability Requirements

This concept can be understood by two usual situations met in using any equipment; it will be ready or not for service in case of requesting at any instant of time. Thus from any item of equipment the accomplishment of a mission without delay and according to its conception is required. In figure 10, the individual elements affecting the quality of this concept are indicated.

Availability is allocated along with the design development and its range must be predicted. The foreseen values have to be confirmed during experimental testing as well as in operation. For availability considerations, in Table 7, the time elements to take into consideration for availability analysis are described; this must be supported and complemented by figure 7.

3.6.1 The Availability Evaluation.

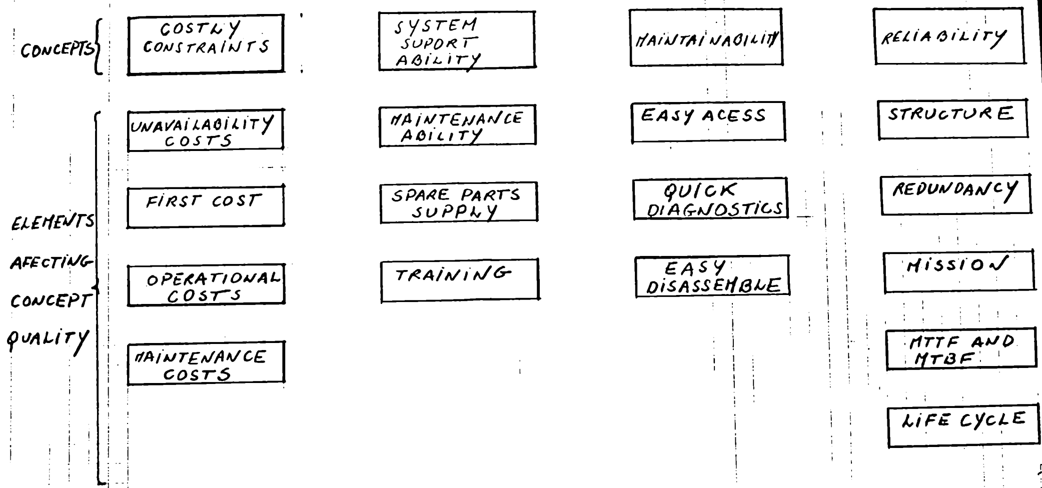
This process is carried out by taking into consideration the following factors:

1. The availability objectives;
2. The data sampling system to support the availability prediction and follow the operational exploitation;
3. The demonstration of the availability specified at the design phase.

Under the first point, the availability objectives are associated with the maximum efficiency of the mission, minimum down time and the optimization of overall costs. These objectives are performed taking into consideration the following:

- Acceptable configurations and layout of both equipment and systems;
- Use of the correct technology;
- Reliability parameters;
- Operational loads;
- Thermodynamic parameters;
- Safety protections;
- Minimization of the logic failure chain;
- Access to the equipments / systems;
- Diagnostics methods and the chosen tests;
- Margins in degraded conditions of operation;
- Level and type of maintenance;
- Personnel ability;
- Process of acquisition and the minimum stock of spare parts.

During the definition of objectives it is also necessary to define the constraints and the dynamic parameters. The constraints are many and can be classified into four groups:


CONCEPTS
COSTLY CONSTRAINTS
SYSTEM SUPORT ABILITY
MAINTAINABILITY
RELIABILITY
ELEMENTS AFFECTING CONCEPT QUALITY
UNAVAILABILITY COSTS
FIRST COST
OPERATIONAL COSTS
MAINTENANCE COSTS
MAINTENANCE ABILITY
SPARE PARTS SUPPLY
TRAINING
EASY ACESS
QUICK DIAGNOSTICS
EASY DISASSEMBLE
STRUCTURE
REDUNDANCY
MISSION
MTTF AND MTBF
LIFE CYCLE

LEVEL TIME ANALYSIS	TOTAL TIME	
1	-TIME REQUIRED	-TIME NON REQUIRED
2	-REAL UP TIME -REAL DOWN TIME	-POTENTIAL UP TIME -POTENTIAL DOWN TIME
3	- OPERATING TIME - STAND BY TIME - INTERNAL DOWN TIME - EXTERNAL DOWN TIME	
4	-TIME TO FAILURE DIAGNOSTICS -DOWN TIME TO MAINTENANCE -TIME TO UP CONDITION AFTER MAINTENANCE	

- Layout constraints;
- Functional constraints;
- Environmental constraints;
- Operational constraints.

The next point defined for the availability evaluation is the data sampling and its treatment. Thus it is possible to carry out the estimation of operational availability. The data necessary in this process include

1. Information about the operational conditions.

   A. Environmental conditions.
   B. Thermal and mechanical constraints.
   C. Operational cycle.
   D. Operational rates of subsystems.
   E. The maintenance factors.

2. Indices of reliability and maintainability and other related factors.

   A. Mean time between failures.
   B. Mean time to repair.
   C. Failure rates.
   D. Critical failures.
   E. Non-critical failures.
   F. Frequency of failures.
   G. Failures due to mechanical factors.
   H. Failures due to thermal factors.
   I. Initial failures.

3. Data on the procedures and time operations in maintenance.

At this point it is necessary to note how the maintenance is done and how long it takes. This includes the type of maintenance, corrective or preventive, and the time definition of the maintenance operations: verification, diagnostics, components replacement / repair and control. It is also necessary to collect the administrative times of maintenance.

The availability demonstration is carried out by using several testing methods. Generally, the conditions of testing defined in advance are:

- The minimum values of the parameters on testing.
  Definition of limits of confidence.
- Number of the elements to test.
  Time for testing.
- Environmental conditions.
  Constraints.

The availability quantification of equipment must be confirmed in the field operations. The data to be collected include:

- Up time discrimination;
- Time of unavailability; time discrimination and related events;
- Classification of failures;
- Costs.

The Assessment of Reliability

4.1 - The Probability Concept in Reliability

Probability means expectancy of an event occurring. Mathematically probability cannot be represented as a subjective concept but as indices between 0 and 1. On the mathematical scale this means absolute impossibility and absolute certainty. This can be extended to the idea of failure and success.

From the above the very basic implications in probability can be deduced:

$A=n/N$

$B=f/N$

$N=n+f$

$A+B=1$

n - number of successful events
f - number of failed events
N - total number of events
A - probability of success
B - probability of failure

The concept of probability can be understood by the example developed in the following pages (Tables 4, 5, 6 and 7). In this example the binomial probability, providing the number of trials and the desired probability of success on each trial is calculated. The skewness and

BINOM

This program calculates and prints Binomial probabilities:

1. Exact Binomial probabilities
2. Right-tail cumulative Binomial probabilities
3. Left-tail cumulative Binomial probabilities

You will be asked to provide two Binomial model parameters:

n = number of trials
p = probability of success on each trial

Printing is suppressed if probabilities become very small in order to shorten the table.

```
How many trials (n)?
The value of n must be a positive integer.
How many trials (n)? 10
What is the probability of a success (p)? 0.01
For this model, skewness =  3.115 and kurtosis = 12.501
```

BINOMIAL PROBABILITY TABLE

n = 10 = number of tries
p = .01 = probability of success on each try
r = number of successes in 10 tries

r	Exact P(X=r)	Cumulative P(X>=r)	Cumulative P(X<r)
0	0.9044	1.0000	0.0000
1	0.0914	0.0956	0.9044
2	0.0042	0.0043	0.9957
3	0.0001	0.0001	0.9999

Probabilities less than .0001 have been omitted.

Table 4

BINOM

This program calculates and prints Binomial probabilities:

1. Exact Binomial probabilities
2. Right-tail cumulative Binomial probabilities
3. Left-tail cumulative Binomial probabilities

You will be asked to provide two Binomial model parameters:

n = number of trials
p = probability of success on each trial

Printing is suppressed if probabilities become very small in order to shorten the table.

How many trials (n)? 10
What is the probability of a success (p)? 0.1
For this model, skewness = 0.843 and kurtosis = 3.511

BINOMIAL PROBABILITY TABLE

n = 10 = number of tries
p = .1 = probability of success on each try
r = number of successes in 10 tries

r	Exact P(X=r)	Cumulative P(X>=r)	Cumulative P(X<r)
0	0.3487	1.0000	0.0000
1	0.3874	0.6513	0.3487
2	0.1937	0.2639	0.7361
3	0.0574	0.0702	0.9298
4	0.0112	0.0128	0.9872
5	0.0015	0.0016	0.9984
6	0.0001	0.0001	0.9999

Probabilities less than .0001 have been omitted.

Table 5

BINOM

This program calculates and prints Binomial probabilities:

1. Exact Binomial probabilities
2. Right-tail cumulative Binomial probabilities
3. Left-tail cumulative Binomial probabilities

You will be asked to provide two Binomial model parameters:

n = number of trials
p = probability of success on each trial

Printing is suppressed if probabilities become very small in order to shorten the table.

How many trials (n)? 10
What is the probability of a success (p)? 0.25
For this model, skewness = 0.365 and kurtosis = 2.933

BINOMIAL PROBABILITY TABLE

n = 10 = number of tries
p = .25 = probability of success on each try
r = number of successes in 10 tries

r	Exact P(X=r)	Cumulative P(X>=r)	Cumulative P(X<r)
0	0.0563	1.0000	0.0000
1	0.1877	0.9437	0.0563
2	0.2816	0.7560	0.2440
3	0.2503	0.4744	0.5256
4	0.1460	0.2241	0.7759
5	0.0584	0.0781	0.9219
6	0.0162	0.0197	0.9803
7	0.0031	0.0035	0.9965
8	0.0004	0.0004	0.9996

Probabilities less than .0001 have been omitted.

BINOM

This program calculates and prints Binomial probabilities:

1. Exact Binomial probabilities
2. Right-tail cumulative Binomial probabilities
3. Left-tail cumulative Binomial probabilities

You will be asked to provide two Binomial model parameters:

n = number of trials
p = probability of success on each trial

Printing is suppressed if probabilities become very small in order to shorten the table.

How many trials (n)? 10
What is the probability of a success (p)? 0.25
For this model, skewness = 0.365 and kurtosis = 2.933

BINOMIAL PROBABILITY TABLE

n = 10 = number of tries
p = .25 = probability of success on each try
r = number of successes in 10 tries

r	Exact P(X=r)	Cumulative P(X>=r)	Cumulative P(X<r)
0	0.0563	1.0000	0.0000
1	0.1877	0.9437	0.0563
2	0.2816	0.7560	0.2440
3	0.2503	0.4744	0.5256
4	0.1460	0.2241	0.7759
5	0.0584	0.0781	0.9219
6	0.0162	0.0197	0.9803
7	0.0031	0.0035	0.9965
8	0.0004	0.0004	0.9996

Probabilities less than .0001 have been omitted.

Table 6

BINOM

This program calculates and prints Binomial probabilities:

1. Exact Binomial probabilities
2. Right-tail cumulative Binomial probabilities
3. Left-tail cumulative Binomial probabilities

You will be asked to provide two Binomial model parameters:

n = number of trials
p = probability of success on each trial

Printing is suppressed if probabilities become very small in order to shorten the table.

```
How many trials (n)? 10
What is the probability of a success (p)? 0.5
For this model, skewness =  0.000 and kurtosis = 2.800
```

BINOMIAL PROBABILITY TABLE

n = 10 = number of tries
p = .5 = probability of success on each try
r = number of successes in 10 tries

r	Exact P(X=r)	Cumulative P(X>=r)	Cumulative P(X<r)
0	0.0010	1.0000	0.0000
1	0.0098	0.9990	0.0010
2	0.0439	0.9893	0.0107
3	0.1172	0.9453	0.0547
4	0.2051	0.8281	0.1719
5	0.2461	0.6230	0.3770
6	0.2051	0.3770	0.6230
7	0.1172	0.1719	0.8281
8	0.0439	0.0547	0.9453
9	0.0098	0.0107	0.9893
10	0.0010	0.0010	0.9990

Probabilities less than .0001 have been omitted.

Although the probability theory in this example is a useful and easy tool to apply, its translation for engineering reliability is not an easy task. Probability can be defined more technically as the value around which the frequency of an event oscillates and towards which it tends after an infinite number of trials (ISO 3534). Probability is always associated with reliability meaning the prediction of future behavior of equipment and systems, judging if they will fail or succeed during the operational time.

Application of probability theory techniques to evaluate reliability cannot be explained as a speculative mathematical operation but only a helpful operational tool to complement other techniques. The probability theory is a helper of what must be called the engineering sense, which means, to have above all the complete technical knowledge of the equipment and systems being evaluated. This information must be complemented by:

- Technical identification of the environmental conditions;
- The interface between man / equipment / system;
- The stresses acting on those elements.

Therefore, to get the most from the use of probability techniques in reliability evaluation it is essential to build up an information network adjusted to systems in study. The functions of it are: collect, record and select data either from experimental conditions or operational conditions. Collecting data on the field conditions is a careful operation and the samples must be well representative of the expected operational conditions. In experimental conditions the expected operational conditions must be simulated. However, sampling data of expensive equipment or systems is a laborious task, for example, destructive methods cannot be applied. Therefore, in this equipment an assessment of the hierarchy is made at the subsystem and component level stepping up from lowest level. Then, by deduction, probability can be evaluated.

After the above steps have been made the probability techniques are applied in correct combination with engineering knowledge on the evaluation of reliability parameters.

4.2 The Sampling Process in Reliability

In the reliability evaluation process, as a probability estimation, it would be unrealistic to get data from everything for all evaluations. Usually a sampling process is used of which it is possible to get information of a population with a fair degree of confidence. In very few cases it is possible to evaluate the whole population when its number is small. However this introduces a great degree of uncertainty and consequently the confidence level is low.

The samples must be taken from the equipment respecting the performance parameters defined at the design stage otherwise all data not according must be refused as invalidated. The performance parameters can include among others: stress, load, temperature, pressure, speed, consumption, etc.

It is normal in the sampling process to find some products that do not follow the operational procedures due to, for example, operation in overload which could lead to premature failure. This can be illustrated in table 8.

This Table is a simulation of the engines failures in a fishing fleet of five ships. Ship 5 has shown a higher failure rate. At first sight, it would be an indication of low reliability. However, later investigations detected poor operational conditions, more severe weather conditions, engine overloaded due to the fishing process, and lack of adequate maintenance. From this example the engineering sense [illegible] essential to avoid mistakes in the reliability analysis.

SHIP'S NUMBER	NAUTICAL MILLES	NUMBER OF FAILURES
1	1000	3
2	1500	4
3	2000	6
4	1800	5
5	700	7

Table [illegible]

In summary to get the right information in the sampling process it is essential to know:

1. What kind of information is really needed and how to get it;

2. How to collect, record, file and store that information for easy access at anytime;

3. How to centralize all sources of information;

4. Who should collect that information.

The balance and correct application of these four points is a good way to get the right reliability parameters. There is no standardized system to get and treat that information. However, in some countries there have been attempts to create a national standard on the sampling and processing of information, chiefly based on operational performances. This process requires the participation of all interested agents, for example, National Administration, Manufacturers Association, etc. Meanwhile any company or organization is free to organize its system of sampling and processing according to the needs. From the last decade up to now there have been increasing usage of computer software for sampling treatment and for following the reliability evaluation network.

The sources of information can be divided into two groups:

1. Internal

   A. Research and development

B. Prototype tests
C. Production assessment
D. Failure analysis
E. Acceptance tests and inspections
F. Audit reports
G. Calibration records
H. Instrument error records
I. Field service records

2. External

A. Professional societies
B. Insurance companies
C. Agents's data tests
D. Institutions of technical education
E. Classification societies
F. Users statements, records and reports
G. Standard rules and guidelines.

4.3 - Application of the Reliability Sampling Process in Manufacturing and Development

All the information derived from the mentioned sources will be channeled into increased reliability and related concepts. In fact it is not acceptable to start the conception of new equipment without assessing the available information of the early stages of development of similar equipment. Much of this information should be supported by proven sample testing methods even on standard elements.

In the design phase, if the product is well known in the market, for example, many designers of similar products, not applied high technology in conception, good national and international technical data bases available, high level of standardization so there are many conditions to get a fair reliable product.

However, in the design of high technology equipment when the information is very scarce, it is necessary to make a lot of effort, through research and development, to get an acceptable level of information on the reliability parameters.

In general, in the design phase the information required can be grouped thus:

1. Reliability of each component under specified use: loads, stresses, humidity, speed, vibration, temperature, pressure, environmental conditions, etc;

2. Data about how changes in operational conditions will affect reliability;

3. Identification and classification of possible failures and malfunctions in the normal conditions of operation as well as those due to misuse.

One step further in the product development, the manufacturing phase, allows a lot of valuable information to be gathered either for future developments or as a feedback to the designers. In the manufacturing phase there is a lot of concern about product quality. The sampling procedures are broadly extended as well as statistical implications. However, the information obtained with reliability implications mostly includes:

1. Accuracy and repeatibility of the measuring devices;

2. Machine tool tolerances and adjustments;

3. Specific machine operation which are difficult to control;

4. Qualifications of the personnel in charge of the manufacturing operations and their control;

5. Statistical evaluations of the materials applied in the manufacturing process;

6. Correct information on all the manufacturing procedures;

7. Random conditions leading to the reliability degradation during the manufacturing process.

Below in, figure 11, a supporting example is illustrated. In a manufacturing process a batch of 200 items of diameter specified to 36H8 was sampled. The values measured during control were grouped in fifteen equally spaced ranges of 0.002 mm. From these values some statistics were estimated, such as:

1. Cumulative frequency;
2. Mean;
3. Coefficient of variance;
4. Standard deviation;
5. First, second and third quartiles.

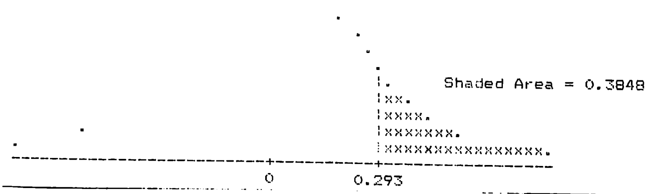
SUMMARY OF CALCULATIONS USING GROUPED DATA

Class	f	m	f*m	$f*(m-\bar{x})^2$	Cum f
36.000 < 36.002	2	36.001	72.0020	.0003535	2
36.002 < 36.004	5	36.003	180.0150	.0006379	7
36.004 < 36.006	7	36.005	252.0350	.0006045	14
36.006 < 36.008	13	36.007	468.0910	.0006916	27
36.008 < 36.010	19	36.009	684.1710	.0005327	46
36.010 < 36.012	27	36.011	972.2971	.0002926	73
36.012 < 36.014	29	36.013	1044.3770	.0000485	102
36.014 < 36.016	25	36.015	900.3750	.0000125	127
36.016 < 36.018	23	36.017	828.3910	.0001682	150
36.018 < 36.020	14	36.019	504.2660	.0003102	164
36.020 < 36.022	15	36.021	540.3150	.0006746	179
36.022 < 36.024	9	36.023	324.2070	.0006820	188
36.024 < 36.026	6	36.025	216.1500	.0006879	194
36.026 < 36.028	4	36.027	144.1080	.0006458	198
36.028 < 36.030	2	36.029	72.0580	.0004325	200
Total:	200		7202.8584	0.0067751	

SUMMARY STATISTICS FOR GROUPED DATA

Mean = 36.01429
St. Dev. = 5.834858E-03 (using sample formula)
St. Dev. = 5.820252E-03 (using population formula)
Coef. of Variation = 0.0 (using sample formula)
Coef. of Variation = 0.0 (using population formula)
1st Quartile = 36.0103
2nd Quartile = 36.01386
3rd Quartile = 36.018

NORMAL PROBABILITY DENSITY FUNCTION



The tolerance quality has its upper limit at 0 and lower at 39 um.
Due to production quality considerations were necessary to change the tolerance quality to H6, that is to say, to keep the same upper limit but decrease the lower limit to 16 um. If the same machine is kept in operation, from the view of quality / reliability, therefore a certain percentage of these items will be discarded. The statistics analysis from the batch shows a normal distribution, being Z, estimated as:

$$Z = D - M / s \qquad Z = 0.293$$

Using a statistics program can be calculated, in figure 11, the bell curve with a shaded area of 0.3848, that is to say, the acceptance percentage is roughly 61.5 of all items on testing. If that machine tool is substituted by one that can keep all items within the tolerances the quality gain would be:

$$GQ = 100 / 61.5 \qquad GQ = 1.63$$

4.3.1 - The Sampling Process in the Operation / Maintenance Phase.

This data is not usually collected using the standard forms therefore some companies or other agents have their own forms internally standardized. These forms generally include:

•

1. Occurrence identification:

   A. Date of occurrence: day, hour and any other temporal identification;
   B. Model of the equipment and its serial number, sales representative and the manufacturer identification;
   C. Reasons for the report.

2. Fault identification:

   A. Symptoms of trouble;

      1. High level of vibration.
      2. High fuel consumption.
      3. High oil consumption.
      4. Intermittent operation.
      5. Leakage.
      6. Overall low performance.
      7. Metal debris in oil.
      8. Noisy operation.
      9. High or low temperatures.
      10. High or low pressure.
      11. Overspeed or speed variation.
      12. Unstable operation.
      13. High or low torque.
      14. Visible defect.

   B. Part condition wear out condition:

      1. Bent.
      2. Blistered or peeled.
      3. Cracked.
      4. Burned.
      5. Changed of characteristics.

6. Wearing.
7. Corrosion.
8. Fracture.
9. Out of adjustment.
10. Clogged.
11. Scored.

3. Cause of trouble:

1. Design deficiency.
2. Faulty maintenance.
3. Faulty assembly.
4. Fluid contamination.
5. Environmental location and weather conditions.
6. Operator.
7. Material fatigue.

4. Corrective actions - repair or modification.

5. Maintenance resources - man-hours, materials and tools / instruments.

6. Control testing.

All this information should be integrated into a OPERATIONAL RELIABILITY ASSESSMENT PROGRAM which would include the following points:

1. Selection of products in operation;

2. Sampling of operational data - sampling methods;

3. Selection and treatment of the input data;

4. Output analysis:

   A. Reliability parameters;
      1. Comparison of the products reliability
      2. Reliability evolution
   B. Detection of the defective components and sub assemblies;
   C. Analysis of failures in frequency and quality.

5. Output data selection and its exploitation:

   A. Corrective actions;
   B. Comparison with the scheduled objectives;
   C. Reliability data bases;
      1. New products redesigned
      2. Definition of warranties in contracts.

4.4 - Approaches for the Operational Reliability Assessment in Marine Industries.

The reliability data sampling has been formally applied in the Navy and naval industries where reliability parameters are very important factors to evaluate the mission efficiency, that is to say, the potential risk expected too.

However, commercial shipping has been reluctant to accept reliability techniques, therefore, in these days shipowners can get high benefits from its wider application. Among others, the following can be pointed out:

Overall improvements in performance and cheaper operations;

Increasing availability;

- Easier maintenance operations;

- Better spare parts management;

- Reduction in supply costs;

- Optimization of new construction orders;

- Increase in performance in older units.

For extended application of reliability concept it is necessary to combine the effort of the following maritime agents:

- Shipping companies.
- Institutes of maritime investigation.
- Maritime academies - Departments of naval architecture and marine engineering.
- Classification societies.
- Shipyards.
- Professional associations with investigation ability.
- The maritime administration.
- Marine manufacturers.

These entities must work in close connection and allocate facilities to centralize information. However, for better organization, management and standardized procedures it would be better to create a so called RELIABILITY COMMISSION or COMMITTEE.

To start the system it would be adequate to elaborate a survey inquest of existing conditions in the fleet. The data sampled using this procedure must be collected in the following situations:

- Ships at sea;
- Ships in port in commercial operations or not;
- Temporary stay at the anchorage;
- Drydocking.

The input information must include the machinery and hull failures and the conditions leading to failure, however, the items included depend on the level and extension of the reliability evaluation. There are also some studies of reliability assessment of specific items or conditions, for example, the Japanese classification society has conducted the inquest survey to investigate the reliability of equipment in unattended machinery space ships.

Generally for the assessment of engine rooms, equipment must be grouped as follows:

1. Main engine;
2. Electrical power generators;
3. Electrical equipment;
4. Automation;
5. Refrigeration equipment;
6. Fuel storage, transfer and treatment;
7. Auxiliary equipment;
8. Shafting and its related equipment;

9. Piping and components;
10. Others.

This must be observed as only a basic guideline and can be applied to general cargo carriers. For specialized ships the list must be carried out according to the diversification of the engine room equipment. Each of those groups is identified as a system and divided into subsystems and elements. The main engine can be analyzed as follows:

1. Air starting subsystem;
   A. Compressor
   B. Control valve
   C. Air starting valve
   D. Air tank

   This subsystem must be very reliable as with its failure the starting process becomes impossible. So it must be very reliable for short times of availability.

2. Mechanical transmission subsystem;
   A. Cylinder connecting rods
   B. Crankshaft
   C. Gear train
   D. Speed governor
   E. Camshaft
   F. Push rods
   G. Rocker arms
   H. Inlet and exhaust valves

   This subsystem rotates the propeller and controls the fuel delivery by a speed governor according to torque. This subsystem has a series connection to the starting subsystem. On starting, its normal operation is only allowed by the former subsystem but in normal operation depends on the capability of the following subsystems

A. Lubricating oil
B. Fuel oil
C. Water jacket
D. Power cylinder
E. Air supply and exhaust

These subsystems are not redundant so the failure of any one implies the total failure of the system. Thus it is necessary to keep the reliability of all these subsystems at a high level.

3. Lubricating oil subsystem;
   A. Oil pump
   B. Oil cooler
   C. Rocker arm lubricating pump
   D. Oil filter
   E. Oil piping
   F. Centrifugal purifier

4. Fuel oil subsystem;
   A. Fuel tanks
   B. Fuel pumps
   C. Filters
   D. Fuel valves
   E. Injectors
   F. Return lines
   G. Viscosity control and regulation
   H. Injector cooling

I. Fuel heaters

5. Water jacket subsystem;
   A. Water heater
   B. Water cooler
   C. Water Pumps

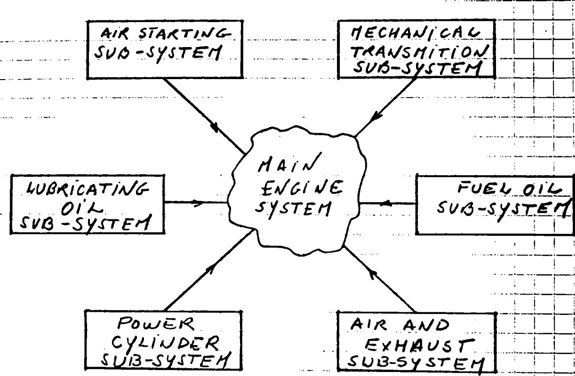
6. Power cylinder subsystem;
   A. Cylinder heads
   B. Cylinder liners
   C. Pistons and cooling
   D. Piston rings

7. Air supply and exhaust subsystem;
   A. Exhaust silencers
   B. Exhaust ducts
   C. Turbochargers
   D. Inlet air filters
   E. Scavanging air cooler.

The interfacing of these subsystems can be seen in figure 12.

In the case of hull assessment it can be divided into the following subsystems:

1. Fore end;
2. Cargo tanks or holds region;
3. Machinery space;
4. Aft end;
5. Rudder;
6. Propeller and its complementary devices.


AIR STARTING SUB-SYSTEM
MECHANICAL TRANSMITION SUB-SYSTEM
LUBRICATING OIL SUB-SYSTEM
MAIN ENGINE SYSTEM
FUEL OIL SUB-SYSTEM
POWER CYLINDER SUB-SYSTEM
AIR AND EXHAUST SUB-SYSTEM

4.5 - Models of Statistical Distribution in Reliability Evaluation of Electronic and Mechanical Equipment

4.5.1 - Introduction

There are several distributions that have been popular in the equipment failure distributions either in experimental testing or in operation. Some of these distributions may have an application according to the flexibility to fit data sampled from discriminated types of equipment, for example, mechanical and electronic equipment. The flexibility of certain distributions are essential for their extended application that is why the Weibull distribution has had increasing popularity among reliability engineers and other people with whom it is concerned.

The distributions referenced in this paper will not exhaust all techniques that can be applied in the reliability analysis. On the contrary, there are many complementary techniques applied according to the specific conditions found. Those chosen are just because of their flexibility, easy fit and wider application.

As a matter of reference the more usual statistical models found in reliability analyse are as follows:

- Exponential;
- Weibull;
- Log Normal;
- Normal;
- Pareto.

In this paper some details of the Weibull and Exponential models are developed. The former has extended application in mechanical equipment and the latter in electronic equipment.

4.5.2 - The Exponential Distribution and its Application

This model is applied to items showing a constant failure rate, that is to say, the equipment whose failure behavior can be allocated to the central part of the bathtub curve for the product lifetime.

In this model it is necessary to consider two parameters: the MTTF (mean time to failure) and MTBF (mean time between failures) which are generally a source of confusion and are identified as the same parameter.

MTTF is applied to items discarded after the first failure without repair and MTBF is applied to repairable items. The MTBF is also wrongly identified as the mission time. After these brief considerations, in figure 13 values of MTTF can be seen (discarded items) which are plotted against the distribution curves of:

- Probability density of failures;
- Failure rate;
- Cumulative failures.

The top graph shows the reduction of the occurrence of failure. However, the decreasing rate is more evident during the early use of equipment. The second graph from the top shows the most common characteristic of the exponential model, the constant failure rate. The last one shows the accumulation of failures with time span.

The exponential model is a good estimation for data available from the following situations:

- Modelling of the flat part of the bathtub curve for life time;
- Products to which the aging and wear out mechanisms have no practical importance;
- Modelling of constant failure rate conditions.

Otherwise it is not a good model for:

Wear out conditions in late life of mechanical items corresponding to the last part of the bathtub curve for life time.

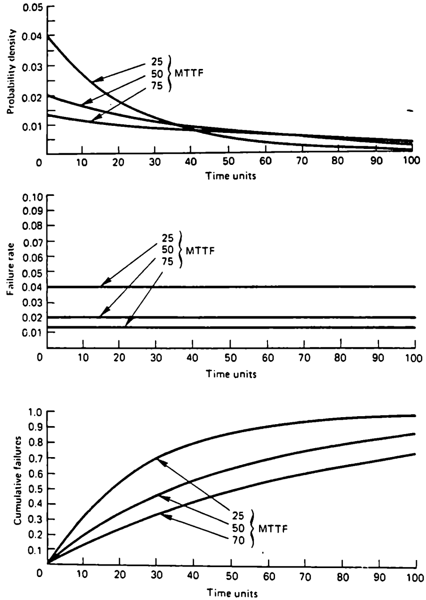
4.5.3 The Exponential Model in Experimental and Operational Testing.

The tests applied can be identified in three groups:

- Exact times with censoring - types I and II
  Readout
  Multicensored.

The last one is typical of the conditions found in operation and can also represent when the failure has more than one cause.

The data collected in testing is fitted to the model with some degree of confidence. This is checked by two



Probability density, failure rate and cumulative failures (= 1 − reliability) for the negative exponential distribution at the mean times to failure (MTTF) marked on the curves

Figure 13

methods:

- Analytical.
- Graphical.

As an analytical method can be applied the chi - square goodness of fit which needs the following steps:

1. Grouping the failure data - Do not need to be in equal ranges;

2. Estimate the frequency of failures implied by the theoretical model - exponential model;

3. Estimate for each group the difference between the expected and observed frequencies;

4. Square the differences and divide by the expected failures;

5. The number of intervals from 1. minus one give the degrees of freedom;

6. Using the tables and the required confidence level the model will or will not be rejected.

It should be pointed out that the method is applied to most of the models referenced for reliability evaluation.
The graphical methods can be classified as:

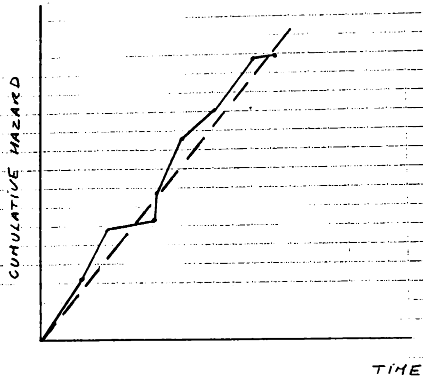
- Histograms;
- Use of special probability graph paper.

The first method has a lack of accuracy but allows the obtaining of approximation curves. To build this model it is necessary to give the following steps:

- Grouping the failure data at acceptable intervals;
  Estimating the percentages for each group;
- Drawing the bar graph;
- Trying to fit the curve to the histogram.

The model will or will not be accepted according to the fitting. The second method, which is much more accurate and of quicker application, uses several types of probability paper to plot the failure data. Generally the acceptance of experimental or operational data by the model depends upon whether the points plotted fit a straight line. This fitting is acceptable on eyeball fit. However, for more accuracy the least - square method must be used.

The graphical method allows several variations. Among them, in figures 14 and 15, it is suggested how to apply the cumulative hazard method. The values plotted are fitted by a dashed straight line being its slope used to estimate either the failure rate or its reciprocal, the MTTF.



FAILURE TIME	FAILURE NUMBER	REVERSE RANK (K)	HAZARD VALUE 100 x 1/K	CUMULATIVE HAZARD
	1	14		
	2	13		
	3	12		
	4	11		
	5	10		
	6	9		
	7	8		
	8	7		
	9	6		
	10	5		
	11	4		
	12	3		
	13	2		
	14	1		

Figures 14 and 15

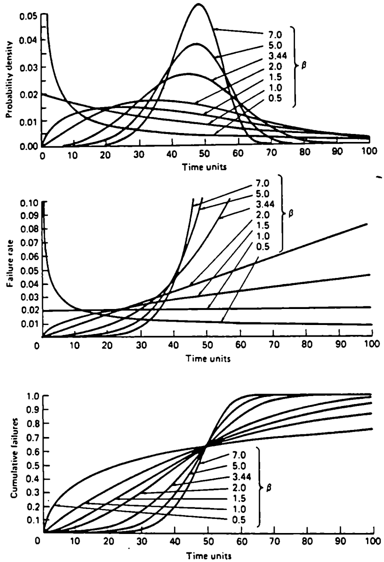
4.5.4 - The Weibull Distribution

This model is very good for analyzing the data distribution in either early failure or in wearout. It is a quite flexible model, therefore, it does not have universal application. This model is characterized by three variable parameters - scale, shape and point location - which gives the flexibility. This model is able to fit the following distributions with more or less a degree of approximation:

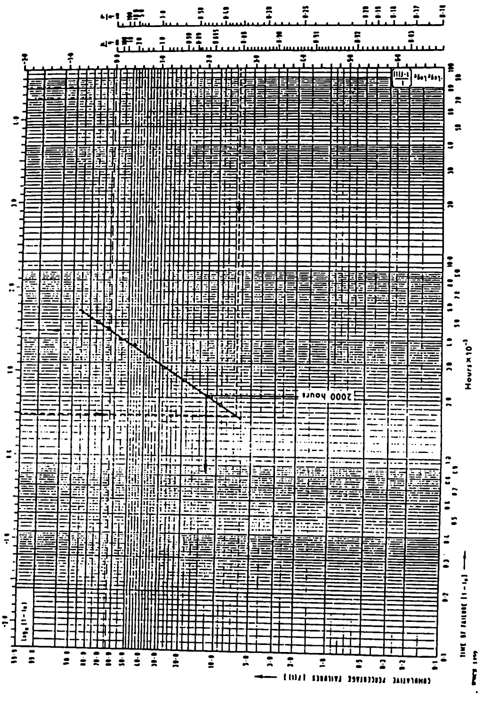
Hyperexponential, associated with early failure;
Exponential, associated with random failures;
Normal, associated with wearout failures found in the late life of the mechanical items. Therefore, in this case there is only an rough approximation;
- Log - Normal, associated with repair or maintenance.

In figure 16, the Weibull functions curves are represented with the variation of shape parameter keeping constant with the scale parameter.

The estimation of the parameters of a distribution is carried out by using a probability paper whose coordinates represent the cumulative percentage failures against the time of failures. Any data following the Weibull distribution must fit a straight line with or without correction. The slope of this line allows the estimation of parameters directly from the scales attached to the paper, see figure 17.



Probability density, failure rate and cumulative failures (= 1 – reliability) for the Weibull distribution at the values of the shaping parameters (β) marked on the curves



Weibull plot of turbine blade failures

Figure 17

If it is not feasible to fit a straight line to the failure data there may be two reasons for this:

- The data does not follow the Weibull model;
- The point location parameter is not zero.

If the last situation is present it is necessary to make some corrections to get a straight line. The rejection of this model sometimes requires the physical inspection of failure because it can be associated to several degraded situations acting together and leading to failure.

4.5.5 - The Weibull Plotting Analysis

Summarized below are some graphs and a brief analysis of each:

1. Linear curve (figure 17)

   From this straight line the following parameters are estimated:

   A. Shape = 2.7
   B. Scale = 4300
   C. Point location = 0

   The value of 2.7 represents a wearout type of failure and the failure rate is increasing linearly.

2. Two straight lines (figure 18)

The plotting of failure data is represented by two concurrent straight lines. In this case the failure data was grouped in different modes of failure leading to estimate two values of the shape parameters - 0.7 and 2.9. The first indicates a hyperexponential distribution which may be due to early failure. The second value is approaching the normal distribution prooving a wearout type of failure and its quick increase.

3. Curved line and its rectification (figure 19)

This plot gave an approximate curved line. To estimate the parameters it is necessary to straighten the curve. This was achieved by trial the location point being obtained at + 1000. This value, the minimum life, was added to all data and the values achieved were replotted.

4. The correct and incorrect procedures for the analysis of data plotted (figure 20)

The upper graph represents the identification of two failure modes by two curves with different shape parameters which gives an intrinsic reliability of 6.5 hours and a shape parameter of 0.45. However, there is one isolated point which is not connected to the other two modes of failure but requires physical inspection. Failing to recognize a failure mode leads to potential unreliability. The lower graph, shows the wrong fitting, different

ignored and a straight line

the value location

factor or intrinsic reliability were eliminated.

fitting the wearout mode

the erosion failure mode.

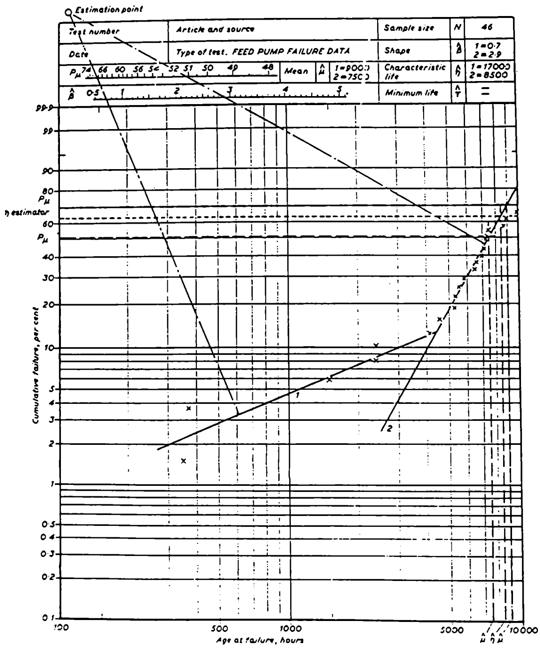
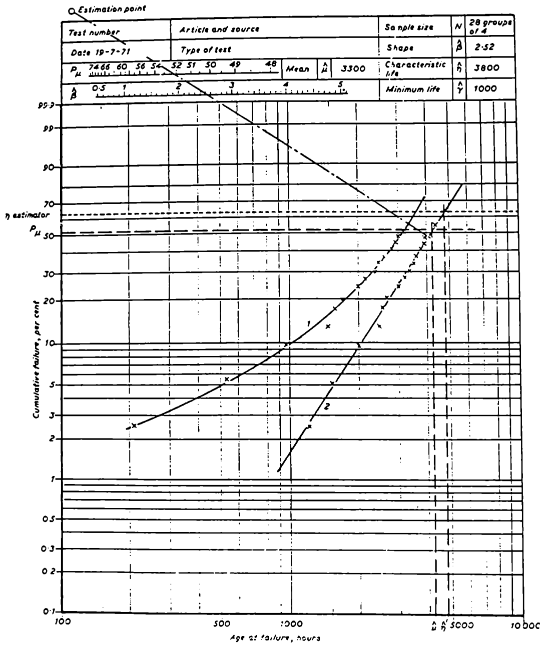
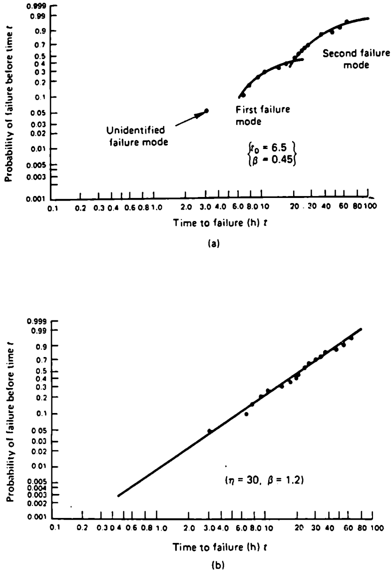


Figure 12


Estimation point
Test number
Article and source
Sample size
N
28 groups of 4
Date 19-7-71
Type of test
Shape
2·52
Mean
3300
Characteristic life
3800
Minimum life
1000
η estimator
Cumulative failure, per cent
Age at failure, hours
100
500
1000
5000
10 000



(a) An example of multi-mode fatigue failure mechanisms. (b) Illustrating how an analysis of the two modes simultaneously can suppress essential features of the process

RECOMMENDATIONS

From the dissertation, some points should be emphasized which need better consideration and evaluation such as:

1. More effort in the design process for the achievement of higher indices of reliability and its related factors granting the conception of higher quality equipment.

2. A correct evaluation of the profit return originated by the introduction of reliability engineering concepts.

3. A correct definition of what reliability data to sampling, the correct definition of failure and defect concepts as the correct understanding of the failure modes.

4. Development of standard methods in the assessment of reliability.

5. The establishment of quick systems for data treatment where the distance of the target, for example, ship / shore communication, does not matter.

6. An improvement of the probability and statistical methods applied in reliability analysis.

7. The broad application of reliability engineering to

assessment of the mechanical equipment following the trend in electronics and automation fields.

8. Combination of RMA to achieve:
   - Better organization;
   - Less costs;
   - Less spare parts;
   - Better management of all resources allocated to maintenance.

9. Improvements in the training and education of operators and maintainers to get the whole intrinsic reliability available in all equipment.

10. Understanding how to gain better advantages in the intrinsic reliability exploitation of existing equipment.

11. Development of RMA in contractual clauses underlining the warranty.

12. Extended standardization of the jargon used in RMA.

13. Evaluation of risks and safety taking into account the RMA concepts.

REFERENCES

Drawings, diagrams and tables have the following references from bibliography section:

- Fig. 1, from 2. E.
- Figs. 2, 3 and Table 1, from 2. C.
- Figs. 4, 5 and 16, from 1. A.
- Figs. 7, 8, 9, 10 and Tables 2 and 3, were adapted from 3. A.
- Fig. 11 and Tables 4, 5, 6, and 7, were made using the computer's program in reference 1. E.
- Figs. 13, 17, 20, from 1. C.
- Figs. 14 and 15, were adapted from 1. B.
- Figs. 18 and 19, from 2. D.

BIBLIOGRAPHY

1. BOOKS

A. Introduction to Reliability Engineering
E. E. Lewis
John Wiley & Sons, Inc.
New York
1978

B. Applied Reliability
Paul A. Tobias and David Trindade
Van Nostrand Reinhold
New York
1986

C. Mechanical Reliability
A. D. S. Carter
Macmillan Education, Ltd.
London
1986

D. Handbook of Reliability Engineering and Management
W. Grant Ireson, Clyde F. Coombs, Jr. Editors
Mc Graw Hill Book Company

E. Exploring Statistics with the IBM PC
David P. Doane
Addison - Wesley Publishing Company

2. TECHNICAL MAGAZINES - ARTICLES - REPORTS

A. Status of Reliability and Maintainability Technology in Use in the U.S. Merchant Marine
National Maritime Research Center
Kings Point
New York

B. Reliability and Maintainability Practices and Procedures Utilized by Selected European Certification Societies for Shipboard Electronic Equipment
National Maritime Research Center
Kings Point
New York

C. Two and Four Stroke Diesel Engines Reliability, Faults and Their Causes, Experienced in the Guarantee Period
H. P. Nielsen and Jorn Drgsted
CIMAC Congress

D. How to Numerate Terotechnology
A. O. F. Venton
Trans. of Institute of Marine Engineers
Vol. 37
1975

E. The Coast Guard - Engineer's Digest
U.S. Department of Transportation
Volume 28
Number 243
Fall 1990

3. STANDARDS ON RELIABILITY

A. AFNOR Standards.